Master's Thesis

Upper Extremity Muscle Activity during Cyclic Push and Pull Task

Haerim Bak

Department of Human Factors Engineering

Graduate School of UNIST

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Haerim Bak

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Approved by

Advisor
Gwanseob Shin

ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

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Haerim Bak

This certifies that the thesis/dissertation of Haerim Bak is approved.

12. 06. 2018

Advisor: Gwanseob Shin

Gwanseob Shin

Sang Hoon Kang

Oh-Sang Kwon

ABSTRACT

Pushing and pulling task is one of the manual materials handling tasks of consumer products and rehabilitation of upper extremity muscles as well as industries. Pushing and pulling task conducted in the sub-maximum level with consumer products or rehabilitation equipment have received little attention compared to that of industry because it does not cause work-related musculoskeletal disorders or injuries. However, dynamic pushing and pulling motions at submaximal levels are enough to cause the muscle fatigue and physical discomforts even though it does not require maximum force or strength level efforts. The primary goal of this laboratory study was to quantitatively evaluate the level of upper extremity muscle activation during cyclic pushing and pulling tasks. The specific aim of this study was to evaluate and compare the relative impact of horizontal and vertical loads on the median and peak activation levels of major upper extremity muscles. Hand grip force and subjective ratings for perceived fatigue and weight felt in hand were also evaluated to explore relationships between the muscle activation level and other measures of physical efforts.

Twenty young healthy females participated in this laboratory experiment. Each task was performing seven cycles of pushing/pulling motions. A total of twelve combinations of three horizontal loads (1kg, 2kg, 3kg), two vertical loads (0.6kg, 1.3kg) and two directions of exertion (push and pull) were performed in randomized order. During each task, muscle activity of seven upper extremity muscles, motions of pushing and pulling, and grip force were observed. After conducting each task, perceived fatigue and weight felt in hand were also measured.

Results showed that muscle activities, hand grip force, and subjective ratings were significantly affected by the horizontal and vertical loads ($p < 0.05$). Most upper extremity and shoulder muscles tested in the current study generated greater activation levels with increased external loads (both horizontal and vertical load) during dynamic pushing and pulling movements, in general. It might be due to their roles in resisting the increased loads and maintaining the stability of motion. Relative effects of each external load on individual muscle varied depending on the role of the muscle and moment induced by each load. Change in the horizontal load more apparently affected the muscles near the shoulder joint, which are known as the primary muscles for pushing/pulling movements. On the other hand, the effect of the vertical load was more apparent for elbow and shoulder flexors to maintain the vertical location of the hand in the changes of the moment at the elbow and shoulder joints. To maintain joint stability, antagonist muscles that do not have major roles for pushing/pulling were more likely to be affected as their agonist muscles being affected by the two kinds of load. Grip forces and

subjective ratings also increased with an increase in external load, complying with the results of muscle activation.

Results of this study provided insights into designing consumer products or rehabilitation programs that include submaximal load level of cyclic pushing and pulling. Also, some considerations for expanding understanding of this study were proposed for future research in dynamic pushing and pulling tasks at submaximal exertion level.

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1. INTRODUCTION

1.1 Research Background

1.1.1 Pushing and pulling tasks in industries

Pushing and pulling task is one of main manual materials handling tasks in many industries. It accounts for nearly half of all manual materials handling tasks (Figure 1) (Hoozemans, Beek, Frings-Dresen, Woude, & Dijk, 2002; Baril-Gingras & Lortie, 1995) and is a major task in various industries such as manufacturing, nursing, agriculture, firefighting (Chow & Dickerson, 2015). According to a report from the National Institute of Occupational Safety and Health (Das & Wang, 2004), pushing and pulling tasks contribute to 20% of all industrial overexertion injuries and are responsible for 5% of all compensable work-related injuries.

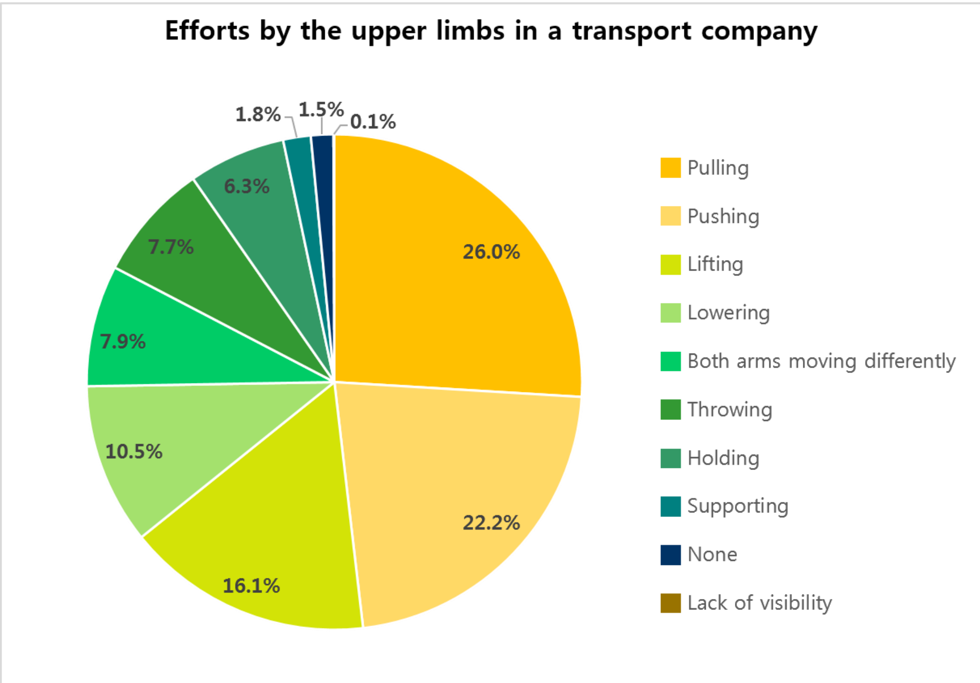

Figure 1. Effort by the upper limbs while handling of objects in a large transport company. (Retrieved from Baril-Gingras & Lortie, 1995)

To address the issues from pushing and pulling activities, previous research in occupational ergonomics has investigated human capability characteristics of pushing and pulling exertions. Human strength data play a pivotal role in ergonomic design; in evaluating musculoskeletal stress and strain from works, in pre-employment screening, equipment design and job placement (Imrhan & Ramakrishnan, 1992). Several factors are known to affect manual push and pull strengths, including direction of exertion, gender, handle height, handle orientation, postural constraints and reach distance (Yoon, Kim, & Kang, 2011; Das & Wang, 2004; Smets, Potvin, & Keir, 2009; Seo, Armstrong, & Young, 2010; Mital & Faard, 1990; Herring & Hallbeck, 2007). Push and pull strengths varied considerably between individuals and conditions, and these differences in strengths provided insight into workstation design that can prevent injuries and disorders from overexertion during pushing and pulling tasks (Figure 2). Seo et al. (2009) reported that the findings of their study would be helpful to improve the safety of works that involve pushing or pulling as well as to increase workers' capability in producing push/pull strengths. Cudlip et al. (2018) also suggested that ergonomists and work task designers should consider interactions between joints of the upper extremity and use these insights to help devise future workstation designs.

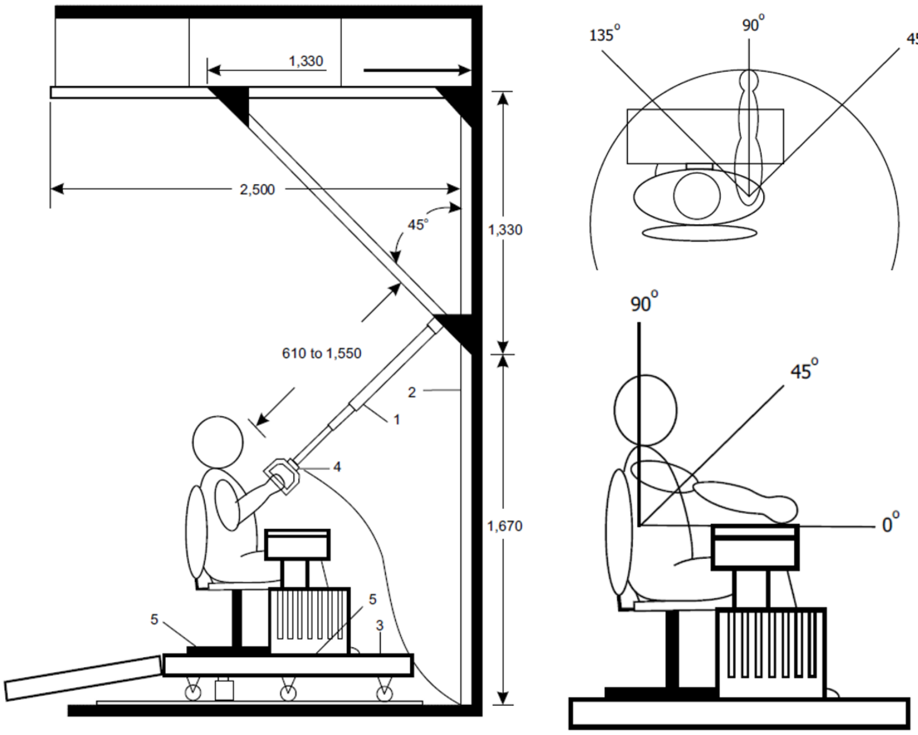

Figure 2. Three-dimensional isometric pull-push strength measurements system for workstation design optimization. (Retrieved from Das & Wang, 2004)

1.1.2 Pushing and pulling tasks in non-industrial environments

Pushing and pulling is a main task for non-industrial applications such as when using consumer products and when performing upper extremity rehabilitation exercises or treatments, as well as for manual materials handling in industries. Some consumer products such as vacuum cleaner and iron require cyclic manual pushing and pulling motions. Users of vacuum cleaners, as an example, conduct cyclic one-hand pushing and pulling strokes during floor vacuuming (Figure 3). For rehabilitation of the upper extremity and shoulder muscles and joints, pushing and pulling motions are also commonly seen. Pushing and pulling motions with elastic resistance are implemented for postinjury and postoperative recovery, injury prevention, and performance enhancement (Hintermeister, Lange, Schultheis, Bey, & Hawkins, 1998), and they are also conducted in robot-aided, force-induced and isokinetic arm training protocols for the upper-extremity motor recovery of stroke patients (Figure 4) (Chang et al., 2007).

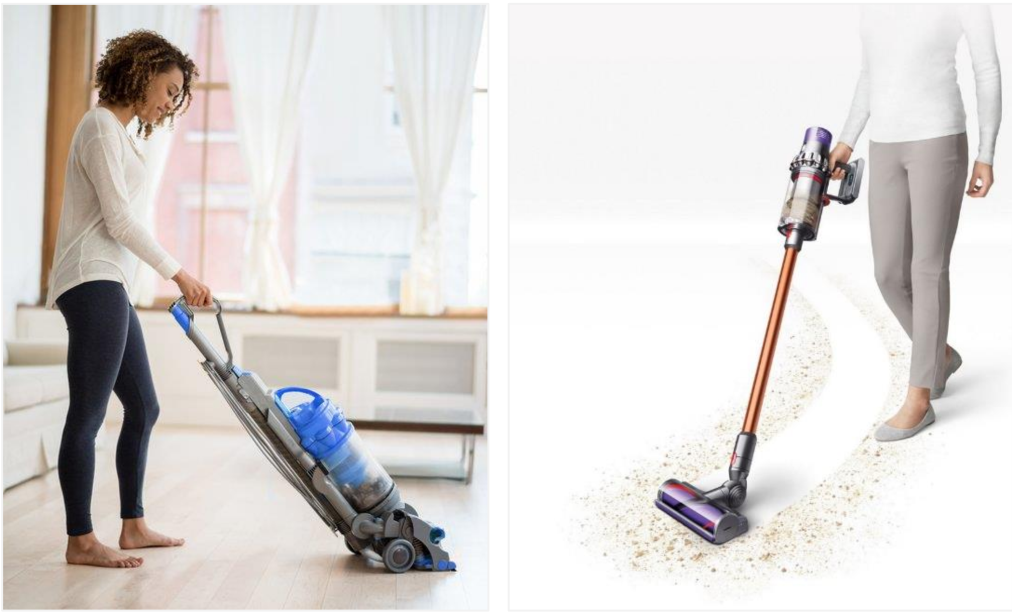

Figure 3. Pushing and pulling tasks in vacuum cleaning.

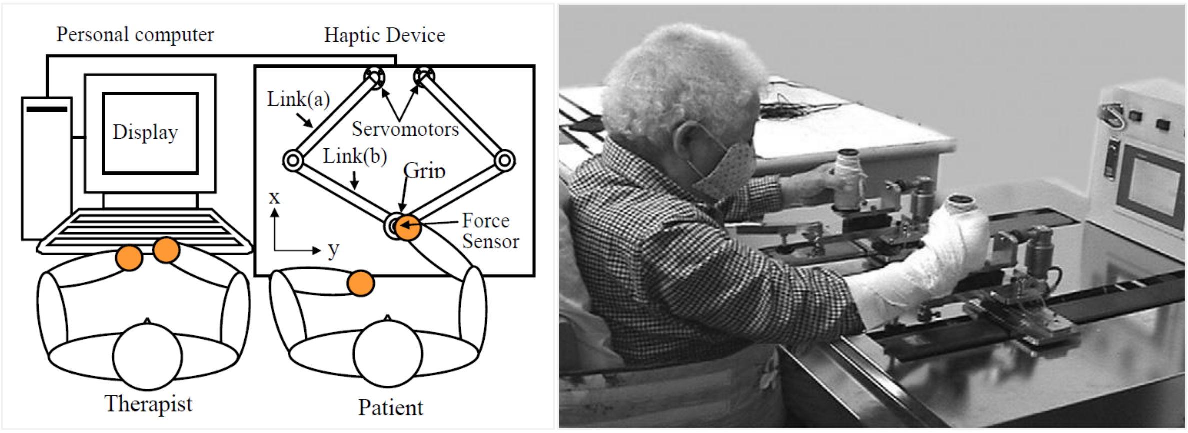

Figure 4. Robot-aided haptic device system (Left) and BFIAMT (Right) for upper limb rehabilitation. (Retrieved from Lee et al, 2011; Chang et al, 2007)

While pushing and pulling activities in industries require workers to generate isometric overexertion or maximal force that induce work-related musculoskeletal disorders and injuries, pushing and pulling tasks in the areas such as consumer products and rehabilitation are conducted with less than the maximum force or strength level effort, in general. Pushing and pulling tasks conducted in the sub-maximum level with consumer products or rehabilitation equipment have received little attention because it does not cause work-related musculoskeletal disorders or injuries. However, there is a need to investigate such submaximal dynamic pushing and pulling tasks in these areas for some reasons, even though it is not directly related to musculoskeletal disorders or injuries.

1.1.3 Reasons for investigating sub-maximum level of dynamic pushing and pulling tasks

Repetitive submaximal loading on muscles generally leads to a reduced functional capacity of the muscle, commonly referred to as fatigue of muscle (Levangie, Norkin, & Lewek, 2011). Even in low force tasks, fatigue is an ongoing process, representing an increase in perceived effort and a reduction in the maximal force generating capacity (Fuller, Lomond, Fung, & Côté, 2009). Gerdle et al. (1989) found that repeated isokinetic shoulder forward flexions with submaximal load caused muscular fatigue for trapezius, deltoids, infraspinatus, and biceps brachii muscles (Figure 5). Kim and Chung (1995) also showed that muscles became fatigued faster for light lifting tasks in high frequency than for heavy lifting tasks in low rate. Therefore, cyclic pushing and pulling motions at low exertion level can induce fatigue of upper extremity muscles. Most users of vacuum cleaner, as an example, vacuum 2-5 times per week and for between 30 minutes and one hour (Electrolux, 2013). Pushing and pulling a vacuum cleaner for 30 minutes or more can cause fatigue as well as physical discomforts, even though the upper extremity muscles do not generate their maximal activation level.

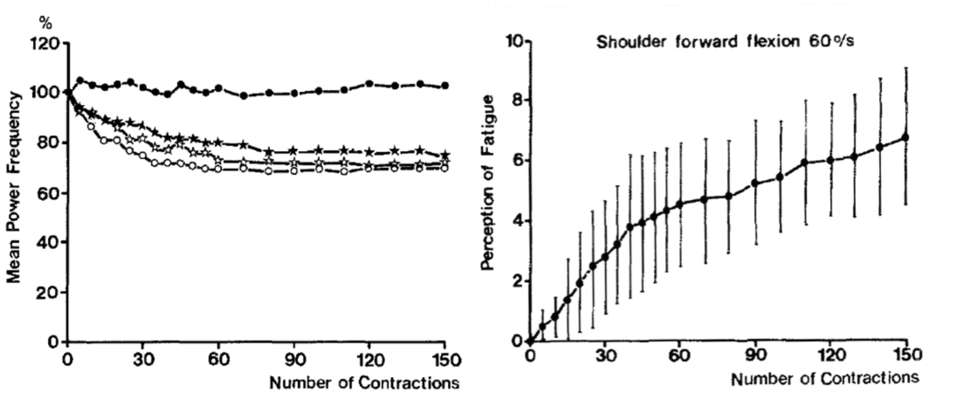

Figure 5. Reduction of mean power frequencies of trapezius (★), the deltoid (○), the infraspinatus (☆), and the biceps brachii (●), indicating caused fatigue (Left). Perceived fatigue during shoulder forward flexion (Right). (Retrieved from Gerdle et al, 1989)

Submaximal pushing and pulling motions in using products or rehabilitation are performed by people who are physically less capable than healthy people on average. Women who are known to have lower push and pull strength (Das & Wang, 2004) tend to vacuum clean more often than men (Bak, D'Souza, & Shin, 2018). Pushing and pulling motions in rehabilitation area are commonly conducted by elderly and patients who have problems with upper extremity. Generally, they have less physical capacity than that of healthy young people who do not have any musculoskeletal disorders on upper extremity. Therefore, when pushing and pulling tasks of these physically less capable population is studied, there are problems in extrapolating the results of previous studies that examined the maximum level of pushing and pulling motions with healthy participants. Until now, ergonomic studies have been focused on reducing work-related disorders or injuries in general, but it should consider kinetics and kinematics of movement used in everyday life and focus on lowering discomforts of populations that have received relatively little attention.

For these reasons, it is necessary to study discomforts induced by sub-maximum level of pushing and pulling motions, rather than studying for preventing injuries that are generated by push/pull requiring maximum strength. Therefore, there is a need to examine reciprocal and dynamic push and pull motions that are conducted at submaximal load based on an understanding of previous studies related pushing and pulling.

1.1.4 Previous studies on pushing and pulling tasks

Previous studies have investigated individual and combined effects of various factors on pushing and pulling tasks. Factors that influence the push and pull tasks are push/pull loads, distal loads, gripping, frequency, handle, and so forth (Keir & Brown, 2012; Chow & Dickerson, 2015; Argubi-Wollesen, Wollesen, Leitner, & Mattes, 2017), and these factors may take part in adjusting the magnitude of external loads during pushing and pulling. As a result of the combination of these various factors, applied external loads acting on the upper extremity can be assumed as two types of fundamental loads; horizontal load and vertical load. However, the individual and combined effects of both horizontal and vertical loads when conducting push/pull tasks have not been fully figured out yet. Keir and his coworkers showed that overall upper extremity muscles activation increased with increased push loads and found that adding only 0.5kg hand load increased upper extremity and shoulder muscles activities in general (Figure 6) (Keir & Brown, 2012; Antony & Keir, 2010). Previous studies examined only one type of external loads, and there was no study about combined effects of both loads during pushing and pulling tasks. However, there is a need to figure out combined horizontal and vertical loads effects on activities of upper extremity muscles. Combined effects of factors are known as higher risks of musculoskeletal disorders (Silverstenin, Fine, & Amstrong, 1986; Moore, Wells, & Ranney, 1991), so it might generate greater fatigue and discomforts. Some actual fields need research that figures out the effects of external loads while pushing and pulling. For example, when designing a vacuum cleaner, developers and designers have tried to control external loads and other design factors that affect external loads so that consumers use the vacuum cleaner with fewer discomforts and fatigue. However, there are only a few studies that have assessed the effect of each external loads on using the products, so two types of external loads effects on push/pull tasks should be considered.

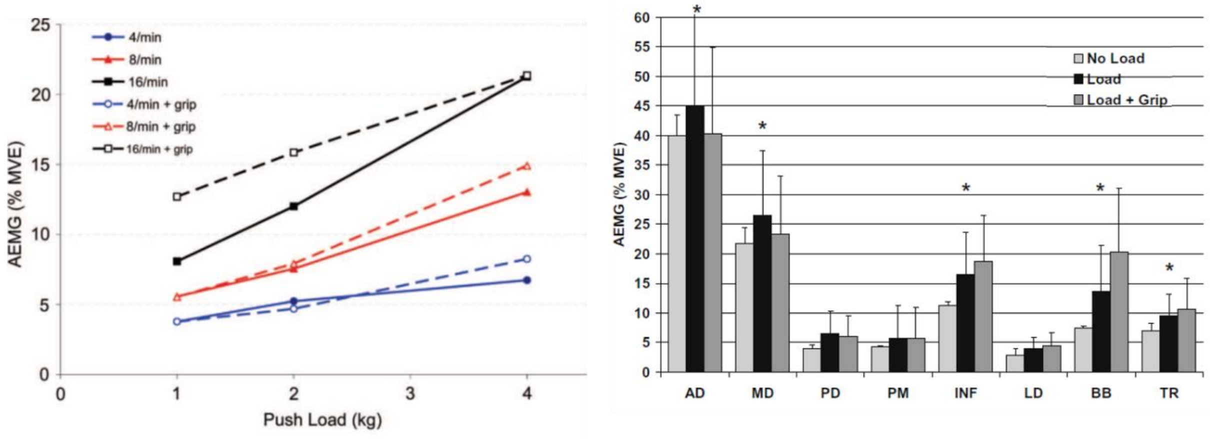

Figure 6. Increased mean anterior deltoid muscle activity with increased push load (Left). Increased mean muscle activity for upper extremity and shoulder muscles by adding 0.5kg handload (Right).
(Retrieved from Keir & Brown, 2012; Antony & Keir, 2010)

The studies on pushing and pulling tasks have concentrated on measuring maximal strength, in general. Factors such as handle orientation, postures of a wrist, elbow, and shoulder, and hand position influenced on manual force strength during maximal voluntary push and pull exertions (Figure 7) (Cudlip, Holmes, Callaghan, & Dickerson, 2018; Seo, Armstrong, & Young, 2010; Kumar, 1995). Until recently, most of the studies on push/pull activities used an isometric mode with a standardized posture for maximizing manual push/pull strengths. However, the effects of the factors on muscle loading have been rarely examined. Understanding the relation between external loads and the internal loads on muscles is essential because submaximal force and fatigue that are investigated by measuring muscle loading can be used to interpret the discomfort of human. Electromyography (EMG) has been commonly used to study the workload and exertion of individual muscles, and amplitude measures, such as the APDF and average EMG, are useful methods for quantifying muscle use. Therefore, external load effects on the workload of upper extremity and shoulder muscles should be studied further to understand the upper extremity muscles activities during sub-maximum level of pushing and pulling.

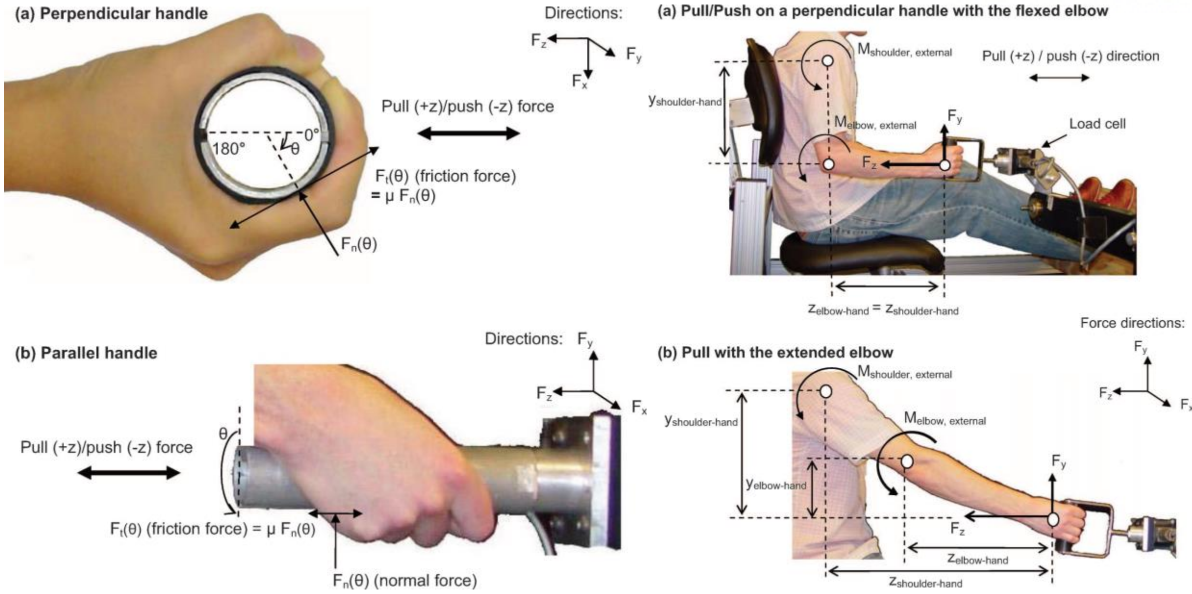

Figure 7. Effects of handle orientation, gloves, handle friction and elbow posture on maximum horizontal pull and push forces. (Retrieved from Seo, Armstrong, & Young, 2010)

Most previous studies have investigated isometric (static) exertions to develop design guidelines for industrial work (Figure 8) (Mital & Ayoub, 1980; Domizio & Keir, 2010; Smets, Potvin, & Keir, 2009; Seo, Armstrong, & Young, 2010). However, there are issues with the applying isometric strength to real cyclic and dynamic push/pull motions that are used in practical, and precautions should be needed when extrapolating the isometric data for dynamic tasks. Isometric strength and muscle loading cannot account for the effect of dynamic movements such as inertial forces and velocities. Many studies showed that significant decline in both push and pull strengths in dynamic exertions as compared with isometric exertions (Figure 9) (Garg & Beller, 1990; Garg, Funke, & Janisch, 1988, Kumar, 1995). Thus, muscle loading while dynamic pushing and pulling may be different to that of static pushing and pulling. Although Keir and Brown (2012) examined the effects of push load, frequency and gripping on muscle activity during dynamic pushing task, the task included only pushing and the frequency (4/min, 8/min, 16/min) also was lower than real reciprocal dynamic push and pull tasks.

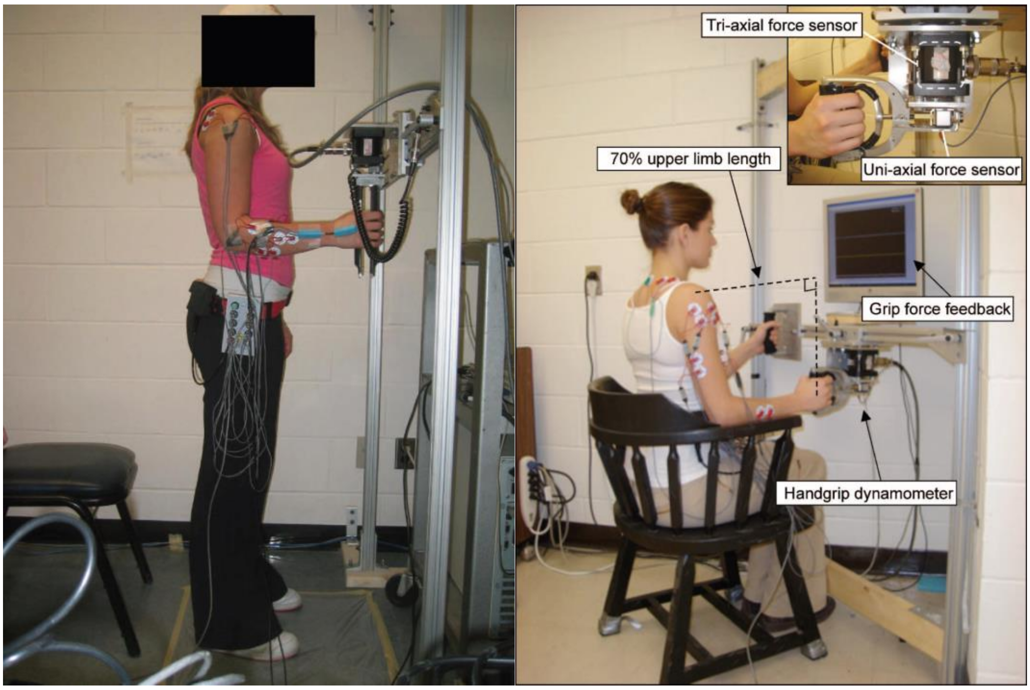

Figure 8. Apparatus used to measure isometric pushing and pulling strength.
(Retrieved from Domizio & Keir, 2010; Smets, Potvin, & Keir, 2009)

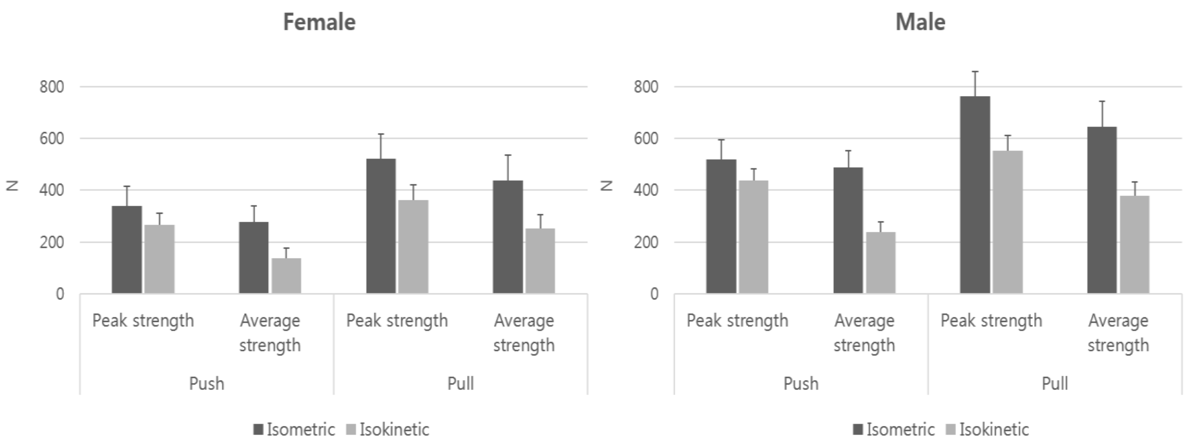

Figure 9. Isometric and isokinetic push/pull strength. (Retrieved from Kumar, 1995)

Most EMG-based studies have investigated upper extremity motions by concentrating on specific body parts such as shoulder (Figure 10) (Antony & Keir, 2010; Macdonell & Keir, 2005; Hodder & Keir, 2012) or wrist (Silverstenin, Fine, & Amstrong, 1986; Malchaire et al, 1997). However, dynamic pushing and pulling motions include moving all shoulder, elbow, and wrist joints, not only specific muscles but all upper extremity muscles together. Besides, muscle not only acts its major role for particular motions but also helps other muscles for stable and delicate movement. For example, although the major role of biceps brachii is flexing elbow joint, it also flexes shoulder and maintains abduction of a shoulder joint in both the supine and semi-prone positions of the forearm (Basmajian & Latif, 1957; Tortora & Derrickson, 2006). Nakhaie et al. (2014) reported that distal parts of arm muscle contraction could activate the muscles of proximal parts that probably require stabilization by proximal muscles to activate distal parts. Therefore, it is necessary to investigate all upper extremity muscle activities that are affected by both horizontal and vertical loads. Besides, the relative effect of each horizontal and vertical load on individual muscle should be considered to understand the role of each muscle during pushing and pulling tasks.

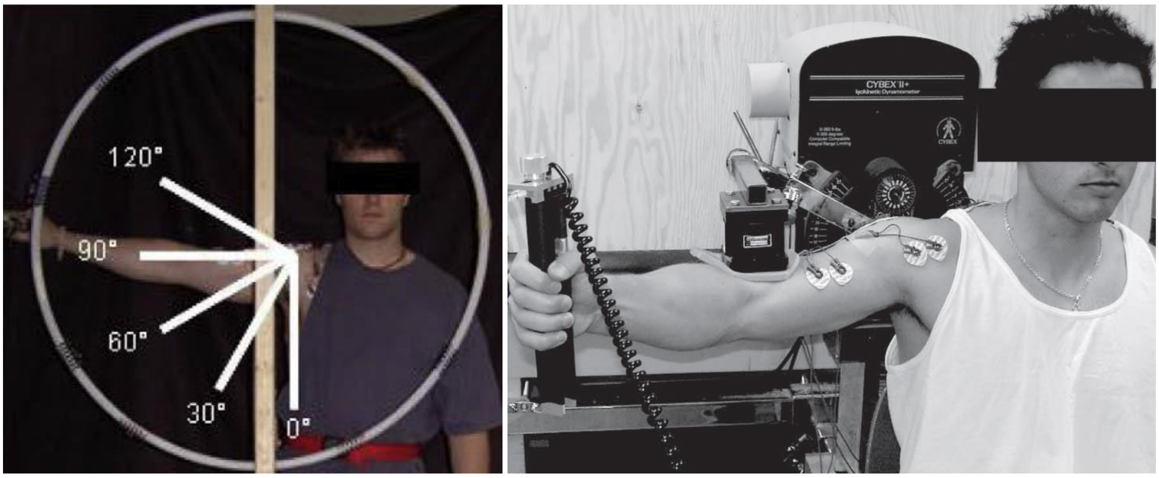

Figure 10. Sensor placement that focused on shoulder muscles.
(Retrieved from Antony & Keir, 2010; Macdonell & Keir, 2005)

In summary, according to the understanding of previous studies related to pushing and pulling tasks, new experiment design is needed because the results of previous studies are not appropriate to be applied to submaximal pushing and pulling tasks that are often used.

Most previous studies on pushing and pulling have concentrated on measuring the maximal strength, and they just predicted the physical demands of submaximal pushing and pulling based on maximum strengths. Also, although most real pushing and pulling tasks have been conducted dynamically and repetitively, previous studies have focused on investigating static exertions of push and pull. Effects of dynamic movements have not been considered in isometric push/pull studies. In addition, submaximal pushing and pulling are usually conducted by people who are less physically capable than healthy people on average. Thus, the pushing and pulling tasks in sub-maximum level may be enough to cause physical discomforts and fatigue even though people do not generate their maximal manual strengths. Therefore, it is necessary to examine submaximal dynamic pushing and pulling motions to understand its physical demands and discomforts, not just focusing on work-related injuries of pushing and pulling tasks in maximum force level.

Consumer products require pushing and pulling motions and the developers and users are interested in ergonomic aspects of the consumer products. However, research about the ergonomics of consumer products is scarce. Recently, few studies evaluated the physical demands of the consumer products. One of the studies on household upright vacuum cleaners found that the amount of muscle activities would be similar to that of occupational tasks that have been known as high-risk ones. Thus, it indicated that there is a need to expand the findings on the physical exposures associated with using consumer products and develop a standardized evaluation protocol for systematic comparisons between various consumer products (Bak, D'Souza, & Shin, 2018). Although previous studies emphasized that understanding the physical demands and perceived fatigue while using consumer products, it has not been well studied and there are no design guidelines for user-friendly consumer products. Thus, the developers just predict how to reduce discomforts of users. Therefore, repetitive pushing and pulling motions with the products that are not designed ergonomically might have potential risks for fatigue, discomforts, and musculoskeletal problems.

Similarly, for rehabilitation of upper extremity muscles and joints, the medical institutes and facilities are looking for objective rehabilitation methods to improve and verify its effects, and some robot-aided rehabilitation programs have been developed for quantitative rehabilitation recently. However, there is no database of upper extremity muscle activation patterns while performing the pushing and pulling motions, so there are some potential issues for conducting rehabilitation. Although patients who have issues with upper extremity have diverse disability levels, it has not been considered when developing rehabilitation devices and training programs. Thus, if a patient continues to perform rehabilitation with inappropriate and higher intensity, muscle, tendon, or soft tissues at the joint areas may be damaged, resulting in discomforts or unexpected injuries. Therefore, it is difficult to continue to rehabilitate the upper extremity due to physical and psychological discomfort and pain.

Therefore, it is necessary to examine submaximal level of dynamic pushing and pulling motions of consumer products and rehabilitation to figure out the issues that were not examined in previous studies. Thus, this preliminary study investigated the effect of two external loads, horizontal and vertical loads, on upper extremity muscles while conducting dynamic pushing and pulling tasks.

1.2 Research Objectives

As explained above, there is a clear need for research regarding dynamic pushing and pulling exertions at submaximal loads. The main objective of this laboratory study was to quantitatively evaluate the level of upper extremity muscle activation during cyclic pushing and pulling tasks. Specifically, it was of interest to evaluate and compare the relative impact of the horizontal and vertical loads on the median and peak activation levels of major upper extremity muscles. Hand grip force and subjective ratings for perceived fatigue and weight felt in hand were also evaluated to explore relationship between the muscle activation level and other measures of physical efforts. This study aims to lay the preliminary groundwork in developing a dose-response relationship between horizontal and vertical loads, and muscle activity. The results should provide insights into muscle loading pattern during combined parameters of horizontal and vertical loads, which can be used to design safer and more efficient products or rehabilitation programs that include submaximal load level of push and pull tasks.

2. METHOD

2.1 Participants

Twenty young healthy participants participated in this laboratory experiment. To minimize the effects of gender, only female participants were recruited. Participants were all right-handed, and their height was controlled 155cm to 168cm. They were screened for any musculoskeletal disorders or discomfort in conducting pushing and pulling movement with loads. All participants had no skin allergic reactions to medical tape and alcohol that were used for attaching EMG sensors on the skin. All participants usually do exercise such as yoga and working out at gym regularly. Before participation, they provided informed consent that was approved by the institutional review board. Table 1 shows information of participants.

Table 1. Participant information, mean (standard deviation).

The number of participants	Age (years)	Weight (kg)	Height (m)	BMI (kg/m^2)
20	22.45 (1.76)	58.65 (9.67)	1.62 (0.03)	22.25 (3.24)

2.2 Instruments

2.2.1 Electromyography (EMG) measurement system

Bagnoli 16-channel Desktop Surface EMG System (Delsys Inc., Boston, MA) and Ag-AgCl non-invasive surface electrodes were used to record myoelectric activity of muscles (Figure 11). For data acquisition, EMG Works 4.0 Analysis software (Delsys Inc., Boston, MA) was used. EMG data were collected at 2000Hz.

Figure 11. Bagnoli 16-channel Desktop Surface EMG System.

2.2.2 Motion capture system

Optitrack Motion Capture System (NaturalPoint Inc., Corvallis, OR) was used to track arm movement while conducting the experiment (Figure 12). Eighteen synchronized cameras were installed around the target capture volume. Each camera emitted infrared light and detected reflected light from reflective markers. Three-dimensional movement data were collected at 100Hz.

Three axes were defined as follow: anterior-posterior axis as X-axis, superior-inferior axis as Y-axis, and medial-lateral axis as Z-axis. Coordinate data of the center of the rigid body for the three axes were recorded. Motive (NaturalPoint Inc., Corvallis, OR) was used for data acquisition and filtering.

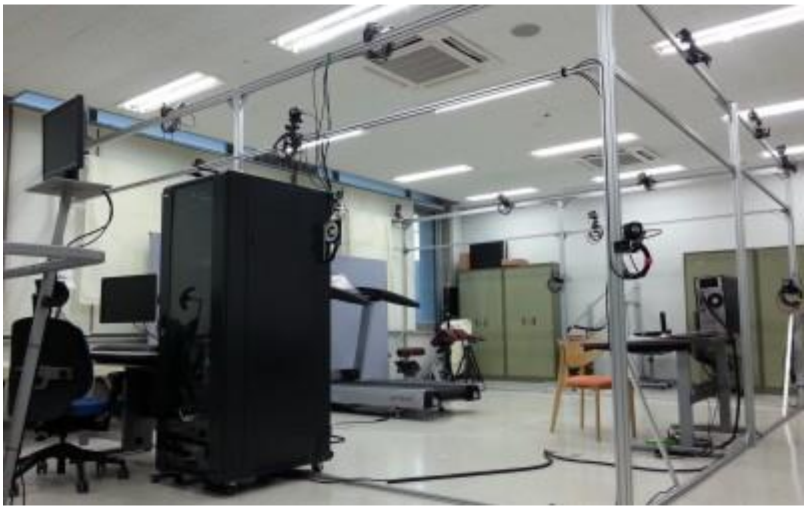

Figure 12. Optitrack Motion Capture System.

2.2.3 Grip force measurement system

Hand dynamometer and Go! Link USB sensor interface system (Vernier Software & Technology., Beaverton, OR) were used to measure grip strength (Figure 13). Grip force data were collected at 10Hz. Logger Lite 1.9.4 (Vernier Software & Technology., Beaverton, OR) was used for data acquisition.

Figure 13. Hand dynamometer

2.3 Experiment design

2.3.1 Experimental variables

The experiment was designed with multiple variables and multiple levels. Independent variables were two types of load; horizontal load and vertical load (Figure 14). The horizontal load had three levels (1kg, 2kg, and 3kg) and mean dynamic load, which were measured by a force gauge, were presented in Table 2. The vertical load had two levels; 0.6kg and 1.3kg which were controlled with the magnet (Figure 15). Both horizontal and vertical load were determined so that participants perform pushing and pulling tasks by using only upper extremity without using other body parts such as waist and legs.

Dependent variables in this study were muscle activity of seven upper extremity muscles (flexor carpi ulnaris, brachioradialis, biceps brachii, triceps brachii, anterior deltoid, posterior deltoid, and upper trapezius), motion of handle (peak acceleration), grip force, and subjective rating for fatigue and weight felt in dominant hand.

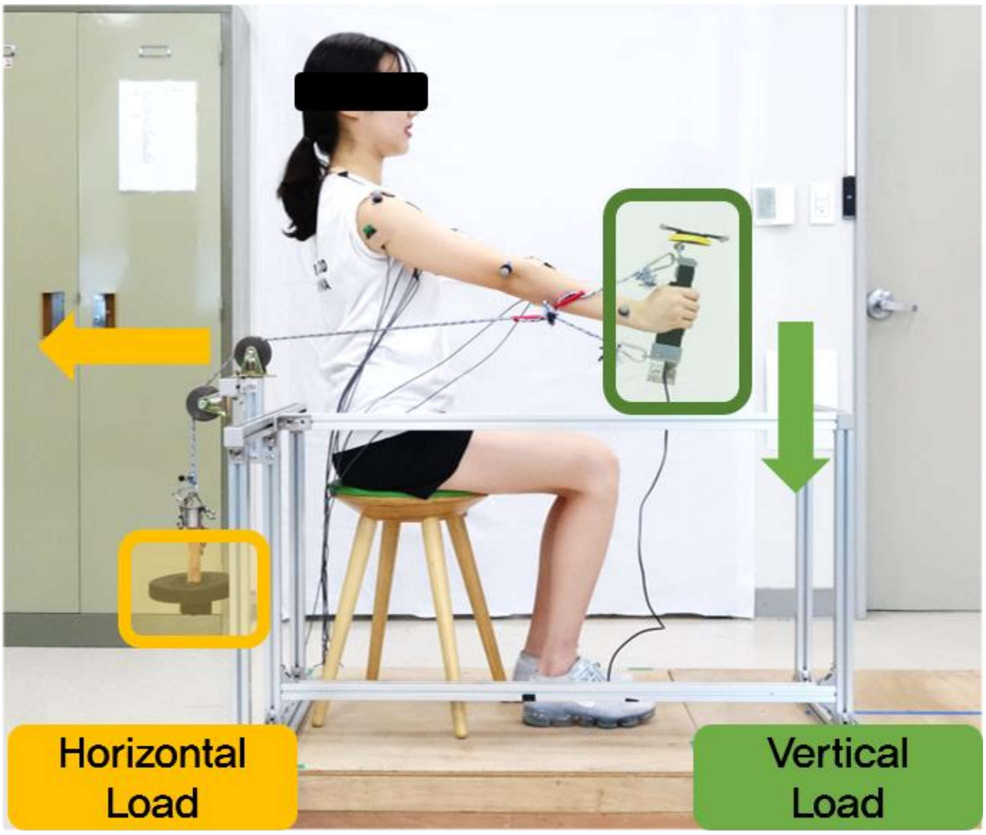

Figure 14. Independent variables; Horizontal load (three levels) and Vertical load (two levels).

Table 2. Horizontal load information, mean (standard deviation).

Levels	Static load		Dynamic load	
	kg	N	kg	N
1	1.00	9.81	1.59 (0.02)	15.59
2	2.00	19.61	2.77 (0.03)	27.16
3	3.00	29.42	4.01 (0.11)	39.32

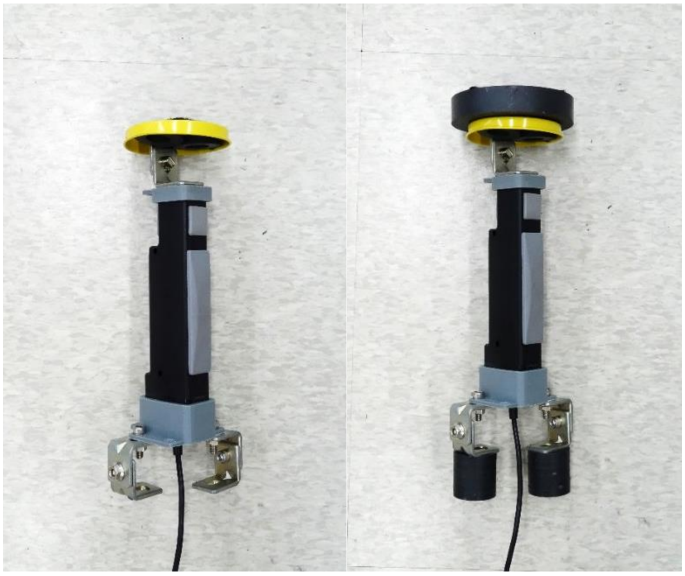

Figure 15. Two levels of vertical loads. Light handle (Left, 0.6kg), Heavy handle (Right, 1.3kg).

2.3.2 Overall procedure of the experiment

This laboratory experiment was conducted in two sessions (Figure 16). Session 1 was a preparation step. It included some basic measurements, skin preparation, sensor attachment, and maximum voluntary contraction (MVC) measurement. In session 1, the experimenter measured the height and weight of the participant and attached sensors. MVC EMG data were collected in session 1.

Session 2 is the main task step. It consisted of training and practicing periods and two main tasks. To reduce the learning effect, sufficient training and practicing periods were given to the participant. After the training and practice periods, the participant conducted two main tasks; Push and Pull. In each task, each participant performed a series of 6 conditions that were combinations of horizontal load and vertical load. Myoelectric activity (EMG) of the seven upper extremity muscles, motion of handle, and grip force were collected during the tasks. A minute break was provided between each condition and 3 minutes break was also given between two main tasks.

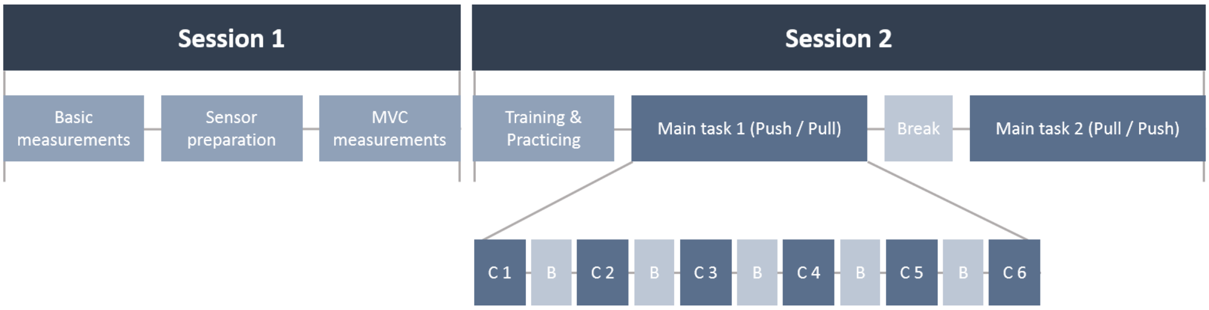

Figure 16. Overall procedure of the experiment. In the main task, C is condition and B is break.

2.3.3 Electromyography (EMG) recording preparation

Before the MVC EMG measurement, the participant was instrumented with EMG electrodes. Prior to the locating EMG electrodes, the participant's skin was cleaned by ethyl alcohol swab to remove dead cell. Ag-AgCl surface EMG electrodes were placed to seven muscles of the dominant arm and shoulder, namely flexor carpi ulnaris, brachioradialis, biceps brachii, triceps brachii, anterior deltoid, posterior deltoid, and upper trapezius muscles (Figure 17). A reference electrode was attached to the right clavicle. Sensor locations were determined according to SENIAM and previous research (Bak, D'Souza, & Shin, 2018). Based on the roles, muscles were determined; pulling (flexor carpi ulnaris, brachioradialis, biceps, posterior deltoid), pushing (triceps, anterior deltoid), weight holding (brachioradialis, biceps, upper trapezius) and overall cyclic shoulder motions (anterior and posterior deltoids, upper trapezius) during reciprocal pushing and pulling tasks. After attaching the EMG electrodes, the participants performed a series of muscle-specific isometric contractions to check electrode placement.

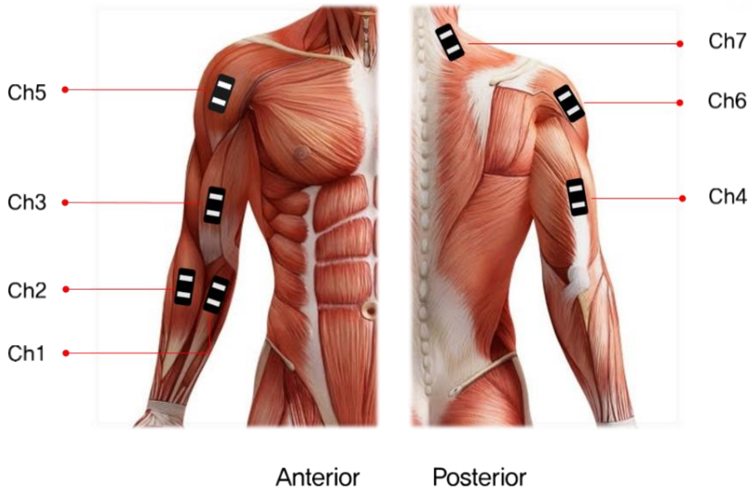

Figure 17. The placements of EMG electrodes. Ch1: Flexor carpi ulnaris, Ch2: Brachioradialis, Ch3: Biceps brachii, Ch4: Triceps brachii, Ch5: Anterior deltoid, Ch6: Posterior deltoid, Ch7: Upper trapezius.

To normalize EMG data during tasks, EMG values of the maximum voluntary contraction (MVC) of all muscles were measured. All MVC EMG data were collected in a seated posture. The MVC EMG of the flexor carpi ulnaris muscle was measured when the participant grabbed the hand dynamometer up to maximum and hold in a 10 seconds trial with the wrist in the neutral position (Figure 18A). Brachioradialis MVC EMG was recorded when the participant was exerting the elbow flexion against a fixed vertical grip with the forearm was parallel to the ground and elbow flexed 90° (Figure 18B). The MVC EMG of biceps brachii muscle was collected in the same posture as the brachioradialis muscle but with wrist supinated (Figure 18C). The triceps brachii MVC EMG was measured when the participant was exerting the elbow extension against stationary support with the elbow flexed 90° (Figure 18D). The anterior deltoid MVC EMG data was collected during the shoulder flexion exertion against the fixed support (Figure 18E). The posterior MVC EMG data was measured as the same as the anterior deltoid muscle but the only direction of exertion was opposite (Figure 18F). The MVC EMG of the upper trapezius muscle was recorded when the participant sat on a chair and pulled up a stationary bar elevating both shoulders with arms straight down (Figure 18G).

MVC EMG data of each muscle was collected twice, and the higher mean amplitude of the two trials was selected as the maximum amplitude of the muscle. Participants had a minute rest after each exertion for recovery.

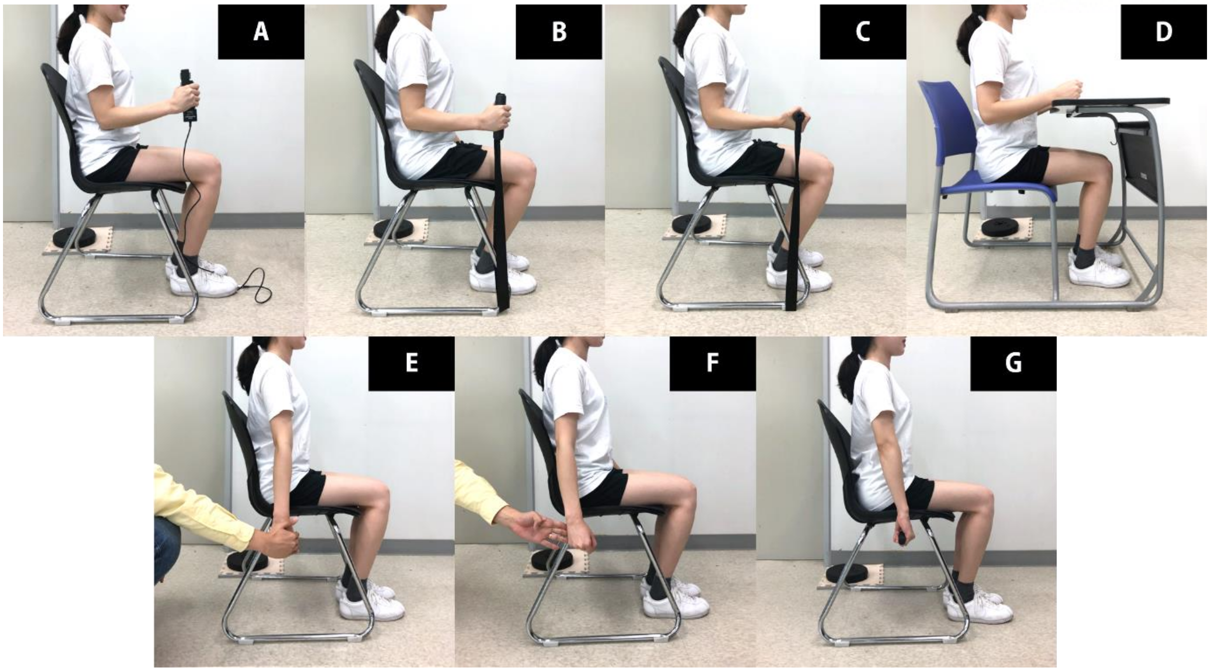

Figure 18. MVC EMG data measurements of each muscle. (A) Flexor carpi ulnaris, (B) Brachioradialis, (C) Biceps brachii, (D) Triceps brachii, (E) Anterior deltoid, (F) Posterior deltoid, (G) Upper trapezius

2.3.4 Motion measurement preparation

Four reflective markers were attached to the top of the handle (Figure 19), and the rigid body was made from the reflective marker set. It was tracked to figure out the coordinates of the handle in three-dimension. Coordinates data of handle were used to guess the motion of push and pull movement.

Figure 19. Reflective marker set on the top of handle.

2.3.5 Grip force measurement preparation

Maximal voluntary grip force (MVG) was measured to normalize grip force data during tasks. MVG was collected using the hand grip dynamometer while the flexor carpi ulnaris MVC EMG recording. Participants exerted maximum grip force with visual feedback. MVG measurements were conducted twice, and MVG was calculated as the highest value among mean of 0.5 seconds window.

2.3.6 Main task

Apparatus

The experimental task incorporated actions and forces that were included pushing, pulling and gripping. A single track was structured with an aluminum frame (Figure 20). The size of the track was designed to fit the mean height of 1.62 m for 20s Korean women based on the Size Korea data (Korean Agency for Technology and Standards, 2015). The track was constructed to include a hand dynamometer (grip span = 5.00 cm) connected to horizontal and vertical load. The handle was connected to an inelastic cable that slides with two low-friction pulleys (Figure 21). The force required to push and pull the handle was altered by weights suspended by the cable over pulleys attached the aluminum frame. The track was fixed at an additional weight for stability.

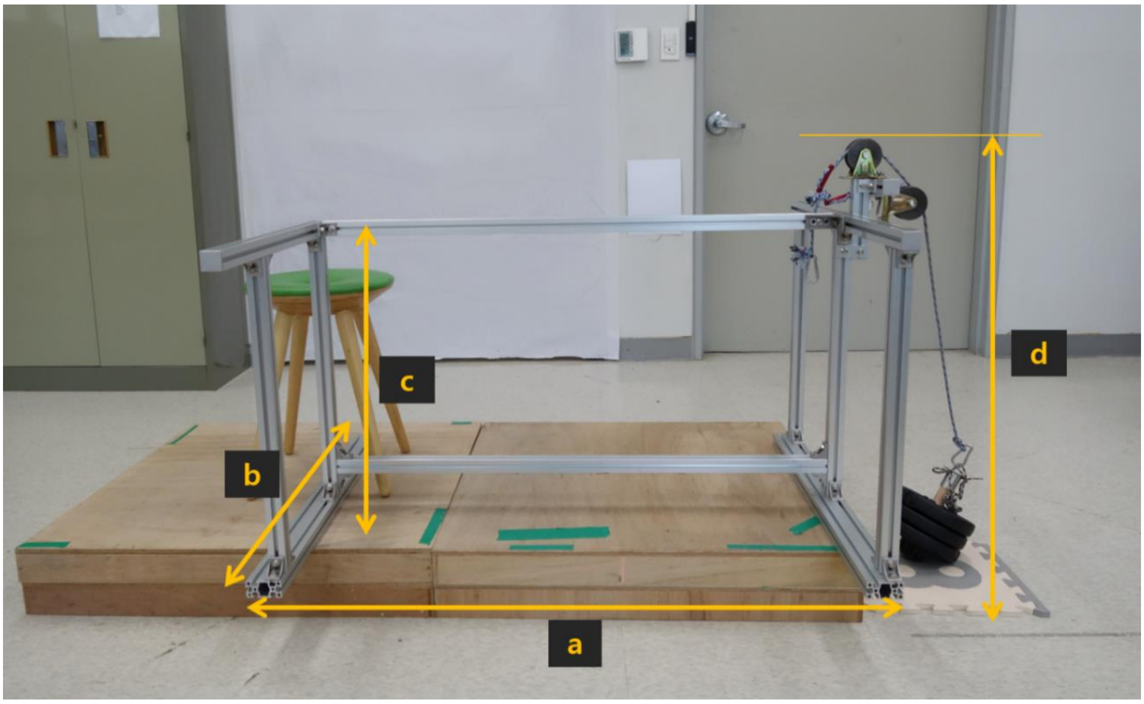

Figure 20. Track for experimental task. (a) Length (1.06 m), (b) Width (0.80 m), and (c) Height of aluminum frame (0.60 m). (d) Overall height of the track (0.88 m).

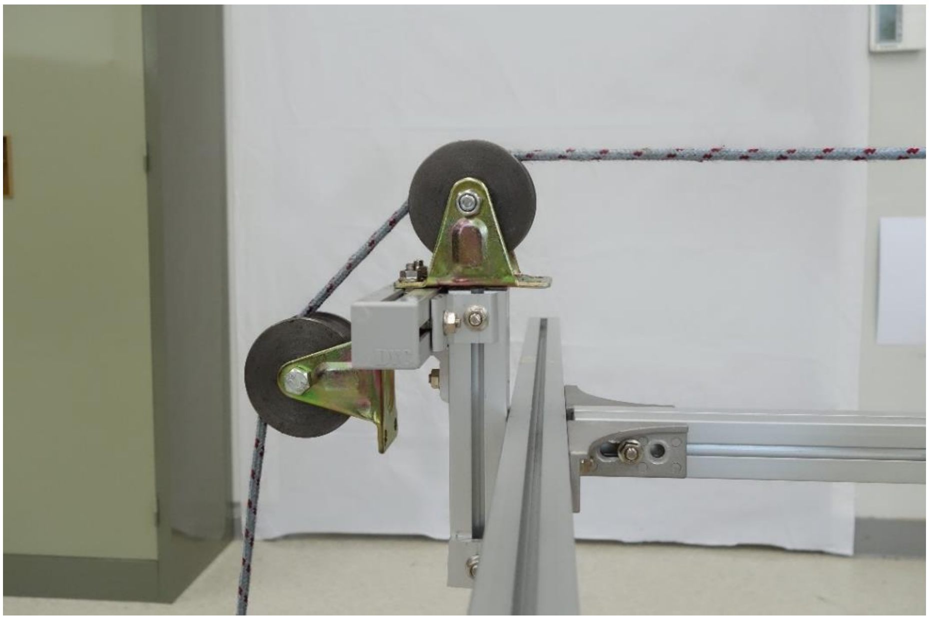

Figure 21. Pulleys attached the aluminum frame.

Testing protocol

After the first session, each participant was trained for conducting experimental tasks in the right posture. Sufficient practice period was also given to minimize potential learning effect. After the training and practicing periods, the participant conducted two main tasks; Push and Pull. In each task, each participant performed a series of 6 conditions that were combinations of horizontal load (1kg, 2kg, and 3kg) and vertical load (0.6kg and 1.3kg). All tasks were conducted in the proper seated posture that supported feet to stabilize balance and minimize use other body parts. Participant was asked not to move or rotate other body segments except the dominant arm. For stable data, the participant was also required to move smoothly so that the horizontal load would not touch the ground.

In the push task, the participant repeated seven cycles of push-pull movements. After grabbing the handle, the participant was asked to position the forearm was parallel to the ground and elbow flexed 90° in the start position and fully stretch the dominant arm in the end position. After pushing, the participant was instructed to retract the arm to the original position for pulling. Participant was asked to allow the handles to return to the start position, no pull effort was required (Figure 22).

The pull task was carried out in the same protocol of the push task, but only exertion and direction of movement was opposite. The participant was instructed to stretch the arm in the start position and flexed elbow in 90° in the end position. After pulling the handle, they were asked to extend the arm to the original position for pushing. No pushing effort was required, and the participant only held the handle for returning to the start position (Figure 23).

Each experimental condition was proceeded with the sound of ‘start’ to ‘end’. EMG of seven muscles, motion of handle, and grip force data were recorded from ‘start’ to ‘end’. The pace of push-pull cycles was controlled to be repeated every 2.82 seconds (2/2, 85 bpm). A metronome sounded to indicate the start and end points of each cycle, using the tablet PC.

Upon completion of each experimental condition, the participant performed the subjective rating for fatigue and weight felt in hand of each task. Fatigue and weight felt in hand were compared to that of conducting the same task with reference weight (2kg dumbbell). Experimenter told the reference as 5-point on the scale. Each participant was asked to rate and rank six conditions on a 0 – 10 scale in terms of fatigue and weight felt in hand. Participants rated high score for the condition that had to feel more fatigue or weight. Participants did not know any information about the weight of horizontal and vertical load and reference dumbbell.

The testing order of six conditions and two tasks (push and pull) were randomized and balanced between participants. About a minute break and three minutes break were provided between each condition and task, respectively.

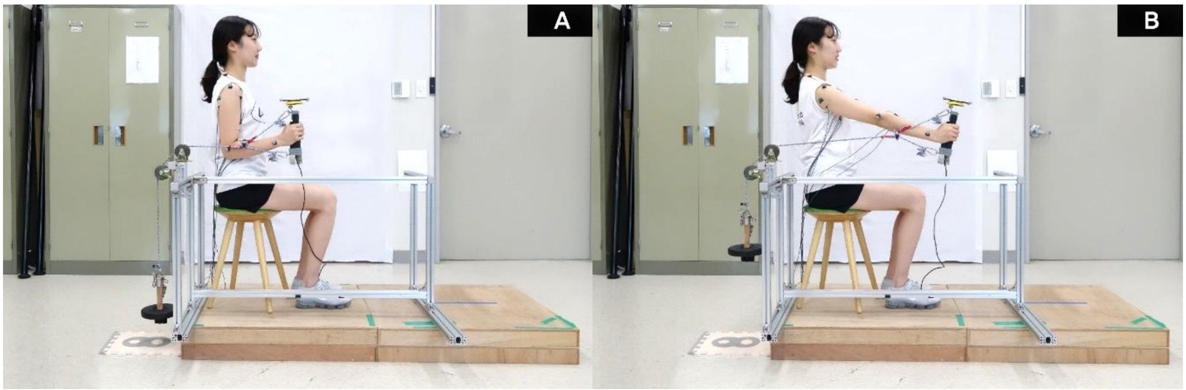

Figure 22. Start (A) and end (B) posture of pushing task.

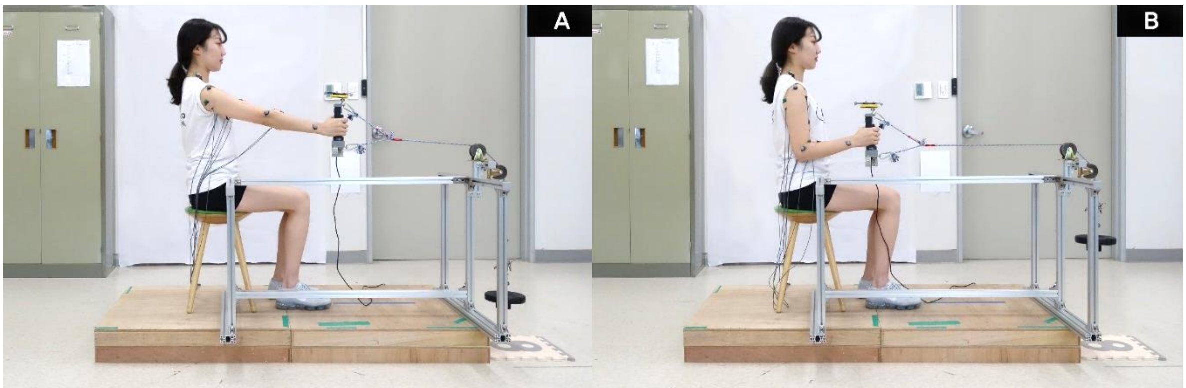

Figure 23. Start (A) and end (B) posture of pulling task.

2.4 Data processing and analysis

2.4.1 Movement tracking

Motive (NaturalPoint Inc., Corvallis, OR) was used for acquisition and filtering of handle movement data. After collecting the movement trajectory data, missed data points were reconstructed by using ‘Fill Gaps’ function that calculated the missing markers trajectory using interpolation methods. The ‘Smooth’ function was also used to filter out unwanted noise in the trajectory signal with a cut-off frequency of 6 Hz.

Trajectory data of handle movement in the sagittal plane was used to divide the motion into exerting and retracting phase when the participant performed each experimental condition. In the pushing task, the exerting phase is pushing the handle, and the retracting phase is the pulling the handle without any exertion. In the pulling task, the exerting and retracting phases were opposite to the pushing task. Only exertion phase data of the middle five cycles were analyzed for each task.

To prove that the participant performed the experimental condition constantly, the acceleration of the handle movement was analyzed. All variables were calculated from the exertion phase of the middle five cycles in each condition. Mean values of peak acceleration while accelerating and decelerating were obtained. The values of acceleration were calculated in the anterior-posterior axis.

2.4.2 Muscle activities

Raw EMG signals were collected at 2,000Hz, bandpass filtered (10-500 Hz), full-wave rectified and smoothed using the 2nd order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Notch filter with 60Hz was used to remove any electrical devices interference. These filtering processes were conducted through the MATLAB program.

Data during the exertion phase was extracted from the filtered data based on the trajectory data of handle movement. The data of the middle five cycles of each condition were extracted for more stable data. The processed data from each muscle were then normalized to the maximum amplitude obtained during a maximum voluntary contraction (MVC). For each condition, the 50^{th} percentile and 90^{th} percentile values of the amplitude probability distribution of the normalized EMG (NEMG) data of each muscle were computed to estimate the median and peak levels of the muscle activation during the tasks.

2.4.3 Grip force

Raw grip force data were collected at 10Hz and data during the exertion phase was extracted based on the trajectory data of handle movement. The data of the middle five cycles of each condition were extracted for stable data. Mean values of each condition were calculated. The processed data were then normalized to the maximal voluntary grip force (MVG).

2.4.4 Subjective rating

For each experimental condition, subjective rating data of fatigue and weight felt in hand were averaged to produce mean subjective rating data.

2.5 Statistical analysis

All data of two main tasks, pushing and pulling task, were analyzed separately. Minitab 18 (Minitab Inc., State college, PA, USA) was used to conduct statistical analysis.

Two-factor repeated measures analysis of variance (ANOVA) was used to evaluate the main and interaction effects of the horizontal load and the vertical load on the dependent variables (Muscle activation, Handle movement, Grip force, and Subjective ratings). Participants variable was regarded as a random factor. Tukey's post hoc analysis tested the statistical differences in dependent variables between each load condition. A significant criterion of $p < 0.05$ was used for all statistical analyses.

3. RESULTS

3.1 Movement tracking

All variables about movement tracking were evaluated for two external loads (Table 3). For pushing task, mean values of peak acceleration while accelerating and decelerating were almost the same (Figure 24). There was no significant effect of horizontal and vertical loads on the peak acceleration. Mean values of peak accelerating while performing the pulling task were similar to that of pushing task. No significant effects of both horizontal and vertical loads were found (Figure 25). When the participants conducted the pushing and pulling task, the handle moved similarly, regardless of horizontal and vertical loads. Significant interaction effects between the two main factors were not found in all peak acceleration for both pushing and pulling tasks.

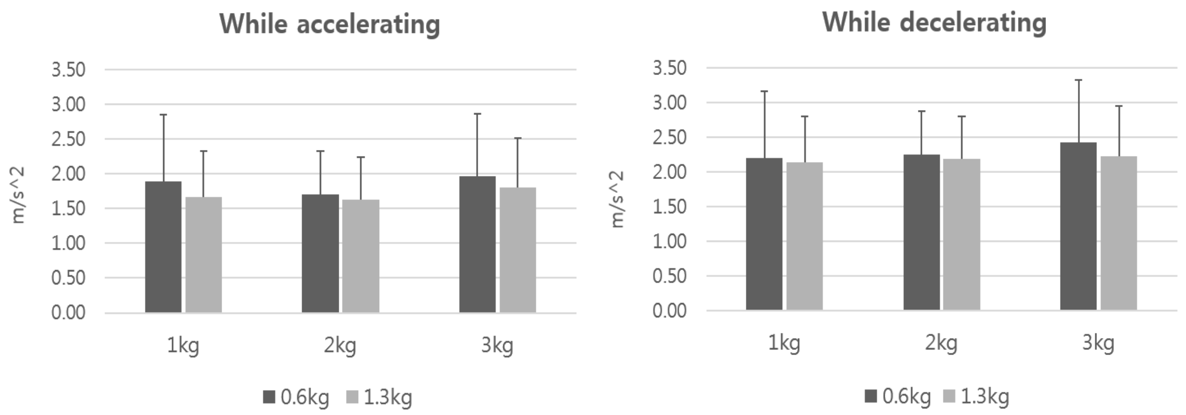

Figure 24. Peak acceleration while accelerating and decelerating of pushing task

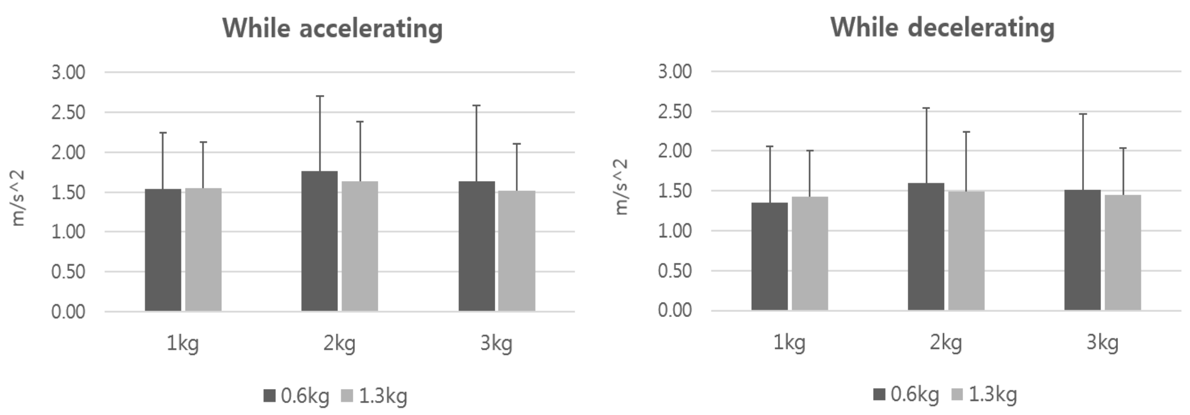

Figure 25. Peak acceleration while accelerating and decelerating of pulling task

Table 3. Peak acceleration when accelerating and decelerating results summary, Mean (standard deviation) across horizontal load (HL) and vertical load (VL).

Peak acceleration (m/s^2)			Horizontal load			Repeated measures ANOVA result (F-value; p-value)		
			1kg	2kg	3kg	HL	VL	HL*VL
Push								
	While accelerating	Vertical load 0.6kg	1.89 (0.97)	1.71 (0.62)	1.96 (0.91)	1.50; 0.229	2.36; 0.128	0.17; 0.840
		Vertical load 1.3kg	1.67 (0.66)	1.63 (0.61)	1.80 (0.72)			
	While decelerating	Vertical load 0.6kg	2.19 (0.93)	2.25 (0.59)	2.42 (0.70)	0.82; 0.445	0.98; 0.324	0.20; 0.818
		Vertical load 1.3kg	2.14 (0.58)	2.19 (0.67)	2.23 (0.60)			
Pull								
	While accelerating	Vertical load 0.6kg	1.54 (0.70)	1.76 (0.94)	1.64 (0.95)	0.80; 0.451	0.61; 0.437	0.19; 0.829
		Vertical load 1.3kg	1.55 (0.57)	1.63 (0.75)	1.52 (0.59)			
	While decelerating	Vertical load 0.6kg	1.35 (0.37)	1.60 (0.90)	1.51 (0.82)	0.90; 0.412	0.11; 0.742	0.31; 0.731
		Vertical load 1.3kg	1.43 (0.45)	1.49 (0.49)	1.45 (0.51)			

3.2 Muscle activities

For pushing tasks, median NEMG (50th percentile) of upper extremity muscles and upper trapezius ranged from 3.15% MVC to 81.74% MVC, and peak NEMG (90th percentile) ranged from 5.17% MVC to 107.52% MVC when conducting cyclic pushing tasks. The two-way ANOVA found that differences in the NEMG levels among the three horizontal loads were significant for all muscles except brachioradialis muscle ($p<0.05$) (Table 4). Subsequent Tukey's post hoc tests revealed that median and peak NEMG of all muscles except brachioradialis were significantly greater for heavier horizontal load. Pushing with the heavier vertical load caused significantly greater activity of all muscles than conducting push movement with the lighter vertical load. Significant difference in vertical load was found for all muscles ($p<0.05$). No significant interaction effects were found between two main factors. Median and peak NEMG data was generally highest in the anterior deltoid muscle during pushing tasks, regardless of both load factors. Performing pushing task with heavier horizontal load and vertical load caused significantly greater muscle activation levels linearly (Figure 26).

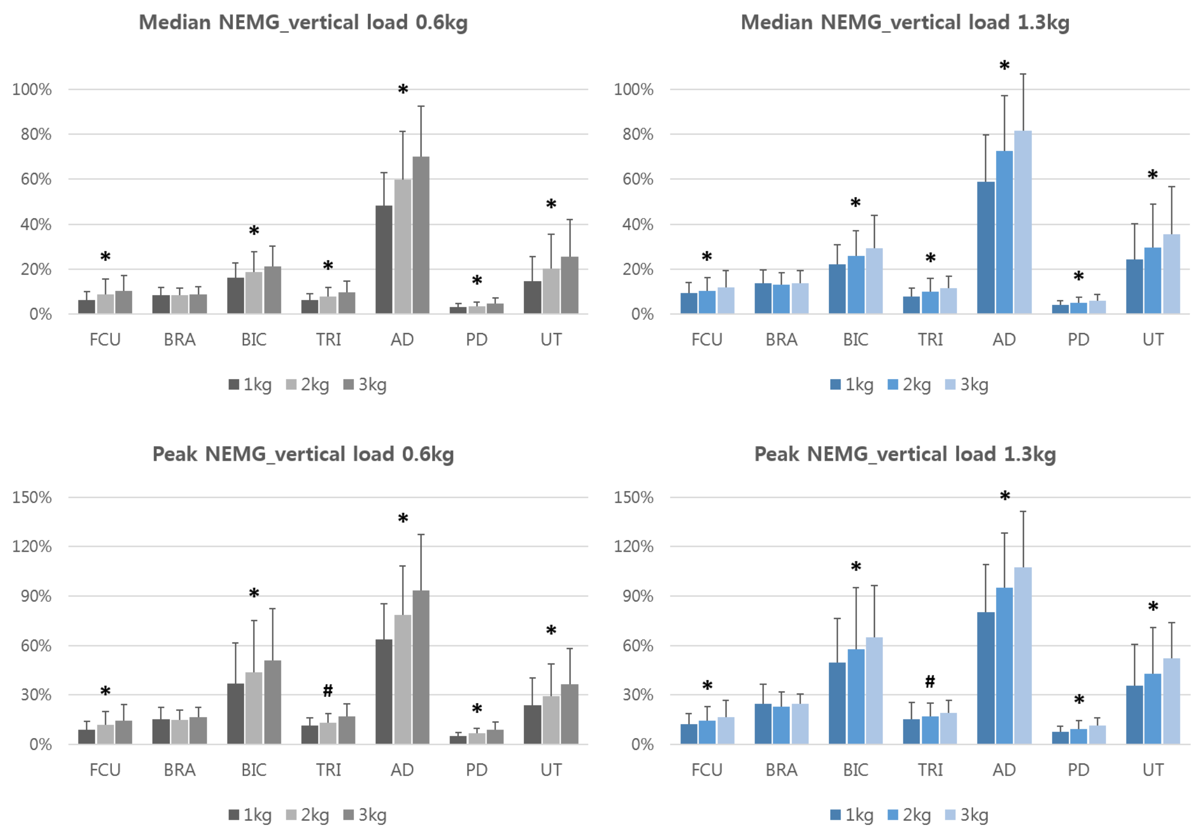

Figure 26. The 50th and 90th percentile NEMG values during pushing tasks. Error bars indicate 1-standard deviation. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius. (*, # indicate results of post-hoc analysis; * : ABC; #: AAB)

Table 4. Results of the statistical analysis for the normalized EMG variables during pushing tasks (F-value; p-value).

50th percentile	Horizontal load (HL)	Vertical load (VL)	HL * VL
Flexor carpi ulnaris	18.86; <0.001	21.51; <0.001	1.24; 0.294
Brachioradialis	0.43; 0.653	243.54; <0.001	0.41; 0.667
Biceps brachii	22.21; <0.001	85.79; <0.001	0.74; 0.480
Triceps brachii	53.17; <0.001	40.35; <0.001	0.44; 0.644
Anterior deltoid	108.23; <0.001	87.94; <0.001	0.23; 0.793
Posterior deltoid	57.03; <0.001	71.77; <0.001	1.68; 0.192
Upper trapezius	37.98; <0.001	87.35; <0.001	0.05; 0.950

90th percentile	Horizontal load (HL)	Vertical load (VL)	HL * VL
Flexor carpi ulnaris	24.71; <0.001	26.68; <0.001	0.43; 0.650
Brachioradialis	1.51; 0.225	107.30; <0.001	0.35; 0.706
Biceps brachii	34.24; <0.001	85.53; <0.001	0.09; 0.914
Triceps brachii	17.32; <0.001	27.61; <0.001	0.85; 0.429
Anterior deltoid	91.32; <0.001	82.98; <0.001	0.23; 0.798
Posterior deltoid	51.03; <0.001	65.77; <0.001	0.26; 0.771
Upper trapezius	26.22; <0.001	69.44; <0.001	0.42; 0.658

During pulling tasks, the values of median NEMG (50th percentile) of upper extremity muscles and upper trapezius ranged from 3.48% MVC to 30.22% MVC, and peak NEMG (90th percentile) ranged from 6.80% MVC to 46.30% MVC when conducting cyclic pulling tasks. Significant main effects of horizontal load were found for all muscles except biceps brachii muscle ($p<0.05$) (Table 5). Subsequent Tukey's post hoc tests revealed that median and peak NEMG of all muscles except biceps brachii muscle were significantly different for horizontal loads. Similar to pushing tasks, pulling the handle with heavier horizontal and vertical loads caused significantly greater exertion of all muscles except anterior deltoid muscle. Muscle activation of anterior deltoid decreased as the horizontal load increased. NEMG values of all muscles except posterior deltoid muscle at the 50th percentile level were significantly different depending on the vertical loads. Between two vertical load conditions, pushing with the heavier vertical load resulted in the greater activity of all muscles except posterior deltoid muscle. Significant interaction effects between the two main factors were also found for the anterior deltoid muscle at the 50th percentile level and for the triceps brachii muscle at the 90th percentile level. Participants generated much greater muscle activation levels of anterior deltoid and triceps muscles when they performed pulling tasks with 1kg horizontal load and 1.3kg vertical load (Figure 27).

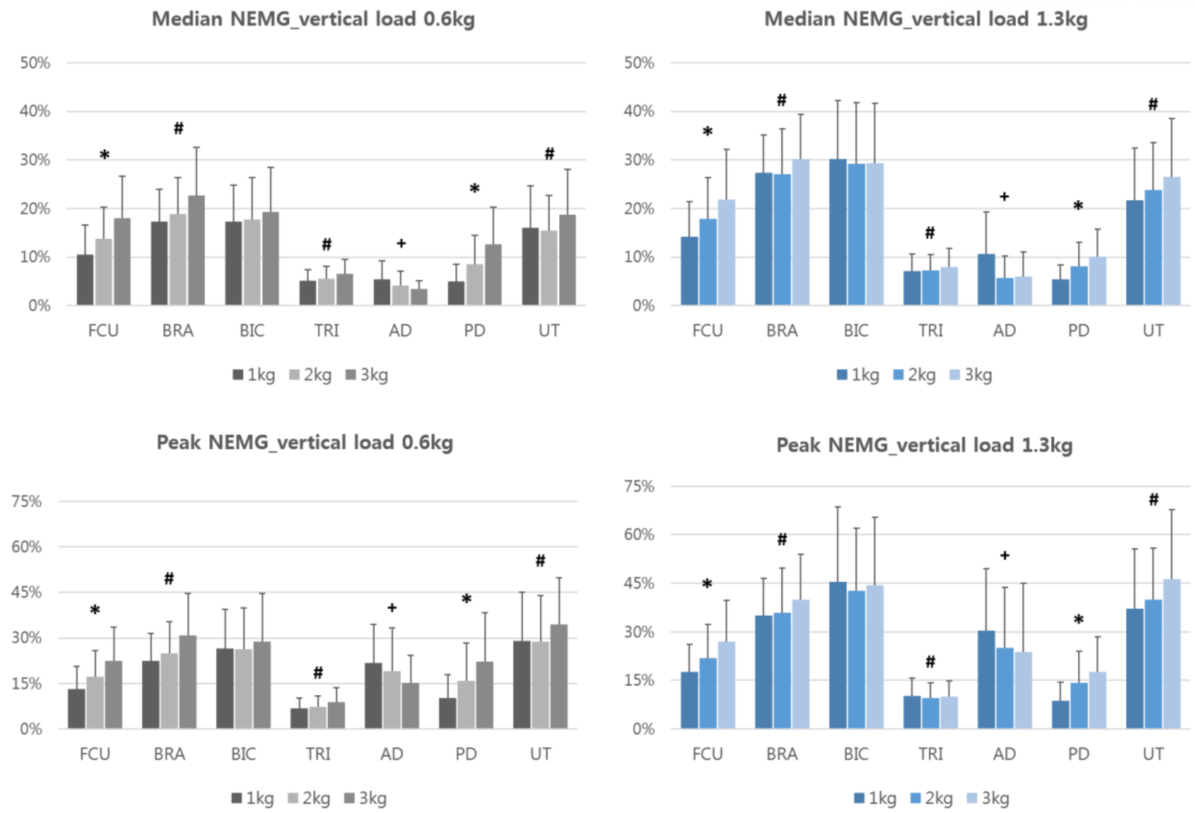

Figure 27. The 50th and 90th percentile NEMG values during pulling tasks. Error bars indicate 1-standard deviation. (*, #, + indicate results of post-hoc analysis; * : ABC; #: AAB; +: ABB)

Table 5. Results of the statistical analysis for the normalized EMG variables during pulling tasks (F-value; p-value).

50th percentile	Horizontal load (HL)	Vertical load (VL)	HL * VL
Flexor carpi ulnaris	84.62; <0.001	67.69; <0.001	0.07; 0.930
Brachioradialis	16.59; <0.001	188.57; <0.001	1.31; 0.275
Biceps brachii	0.46; 0.635	252.53; <0.001	1.27; 0.286
Triceps brachii	17.24; <0.001	107.52; <0.001	1.10; 0.336
Anterior deltoid	14.31; <0.001	30.40; <0.001	3.86; 0.024
Posterior deltoid	52.15; <0.001	2.88; 0.093	3.07; 0.051
Upper trapezius	8.66; <0.001	89.62; <0.001	1.07; 0.346

90th percentile	Horizontal load (HL)	Vertical load (VL)	HL * VL
Flexor carpi ulnaris	88.99; <0.001	63.68; <0.001	0.00; 0.998
Brachioradialis	18.26; <0.001	141.56; <0.001	1.10; 0.337
Biceps brachii	0.86; 0.426	169.23; <0.001	0.56; 0.571
Triceps brachii	4.51; 0.013	43.73; <0.001	3.48; 0.035
Anterior deltoid	8.64; <0.001	35.77; <0.001	0.45; 0.638
Posterior deltoid	39.11; <0.001	7.25; 0.008	1.21; 0.303
Upper trapezius	10.55; <0.001	57.62; <0.001	0.68; 0.508

Effect size, partial eta squared, was calculated based on the results of statistical analysis. The effect size of each load in each muscle was different. During pushing tasks, the effect size of horizontal load was greater than that of vertical load for flexor carpi ulnaris, triceps brachii, anterior, and posterior deltoid muscles. On the contrary, brachioradialis, biceps, and upper trapezius muscles had larger effect size of vertical load than that of horizontal load (Table 6).

Table 6. Effect size of the normalized EMG variables during pushing tasks. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius.

		FCU	BRA	BIC	TRI	AD	PD	UT
50th percentile	Horizontal load	**0.284**	0.009	0.319	**0.528**	**0.695**	**0.546**	0.444
	Vertical load	0.185	**0.719**	**0.475**	0.298	0.481	0.430	**0.479**
90th percentile	Horizontal load	**0.342**	0.031	0.419	**0.267**	**0.658**	**0.518**	0.356
	Vertical load	0.219	**0.530**	**0.474**	0.225	0.466	0.409	**0.422**

While conducting pulling tasks, flexor carpi ulnaris and posterior muscles had the greater effect size of horizontal load, compared to effect size of vertical loads. Similar to pushing tasks, the effect size of vertical load was larger than that of horizontal load for brachioradialis, biceps and triceps brachii, anterior deltoid, and upper trapezius muscles (Table 7).

Table 7. Effect size of the normalized EMG variables during pulling tasks. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius.

		FCU	BRA	BIC	TRI	AD	PD	UT
50th percentile	Horizontal load	**0.640**	0.259	0.010	0.266	0.232	**0.523**	0.154
	Vertical load	0.416	**0.665**	**0.727**	**0.531**	**0.242**	0.029	**0.485**
90th percentile	Horizontal load	**0.652**	0.278	0.018	0.087	0.154	**0.452**	0.182
	Vertical load	0.401	**0.598**	**0.640**	**0.315**	**0.274**	0.071	**0.378**

3.3 Grip force

The normalized grip force of pushing tasks ranged from 6.21% MVG to 38.84% MVG, and it differed significantly ($p < 0.05$) between horizontal load conditions and vertical load conditions (Table 8). In the case of pulling tasks, the normalized grip force ranged from 4.24% MVG to 35.24% MVG. It also differed significantly by both load conditions. No significant interaction effects were found between the main factors.

Conducting with heavier horizontal load caused significantly greater normalized grip force in both pushing and pulling tasks. Similarly, the normalized grip force was significantly higher as the vertical load increases in both pushing and pulling tasks (Figure 28).

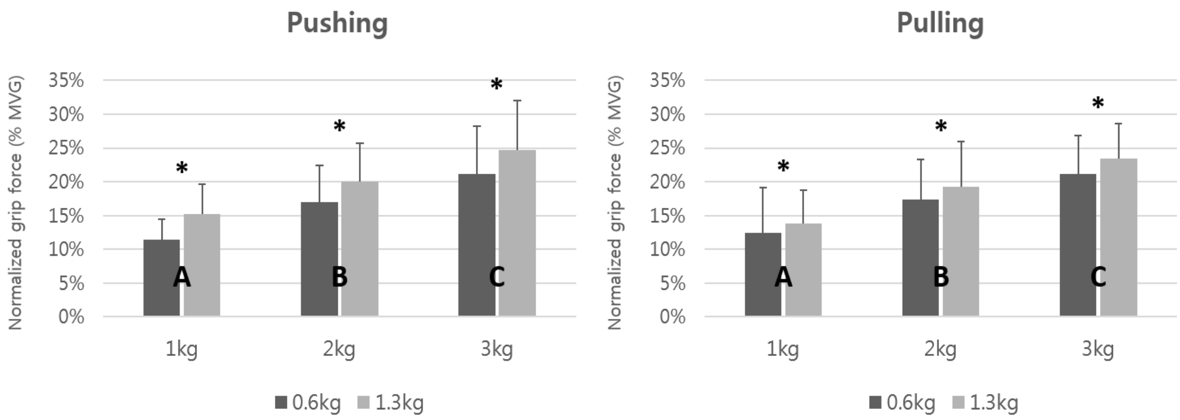

Figure 28. Grip force of pushing task (Left) and pulling task (Right).
(* and bars with different letters indicate significant differences (p<0.05) in post-hoc analysis)

Table 8. Grip force results summary, Mean (standard deviation) across horizontal load (HL) and vertical load (VL).

Grip forces (% MVG)		Horizontal load			Repeated measures ANOVA result (F-value; p-value)		
		1kg	2kg	3kg	HL	VL	HL*VL
Push							
	Vertical load 0.6kg	11.44 (0.030)	17.01 (0.053)	21.12 (0.071)	88.88; <0.001	33.81; <0.001	0.16; 0.848
	Vertical load 1.3kg	15.17 (0.045)	19.96 (0.057)	24.71 (0.073)			
Pull							
	Vertical load 0.6kg	12.46 (0.066)	17.41 (0.059)	21.1 (0.058)	77.83; <0.001	9.77; <0.001	0.18; 0.836
	Vertical load 1.3kg	13.87 (0.049)	19.3 (0.067)	23.38 (0.053)			

3.4 Subjective rating

Mean fatigue and weight felt in hand scores during pushing task ranged from 0 to 10 and from 0 to 10, respectively. Significant effects of both horizontal load and vertical load were found ($p < 0.05$). During pulling task, the values of averaged fatigue and weight felt in hand ranged from 0 to 8 and from 0 to 9, respectively. There were significant effects of two main factors on the subjective rating scores. No significant interaction effects were found between two main factors (Table 9).

In both push and pull tasks, participants reported that they felt less fatigue and lighter weight in hand with lighter horizontal load. Performing the experimental conditions with lighter vertical load also let participants respond less fatigue and weight in hand (Figure 29 & 30). In summary, participants responded that they were more difficult and felt heavier weight in their hand as both loads increased.

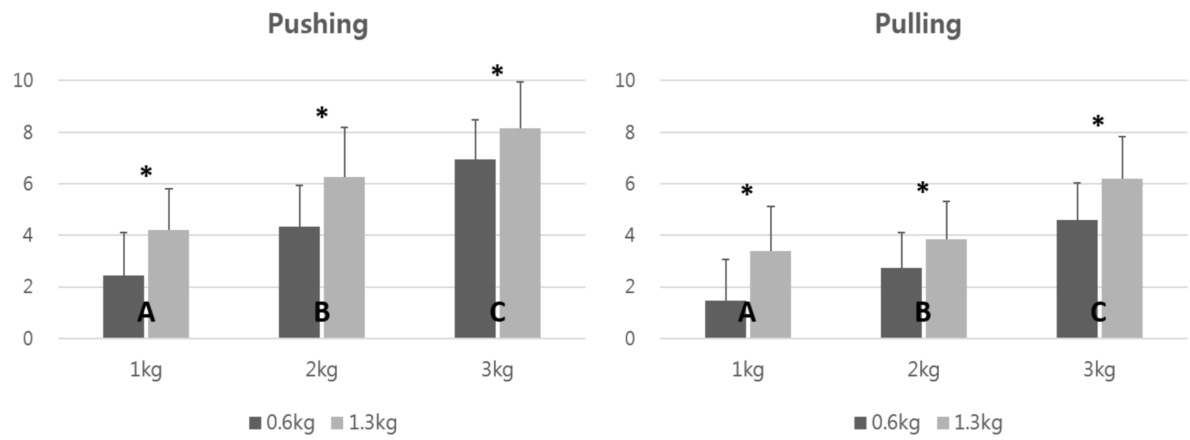

Figure 29. Subjective ratings for fatigue of pushing and pulling task.
(* and bars with different letters indicate significant differences (p<0.05) in post-hoc analysis)

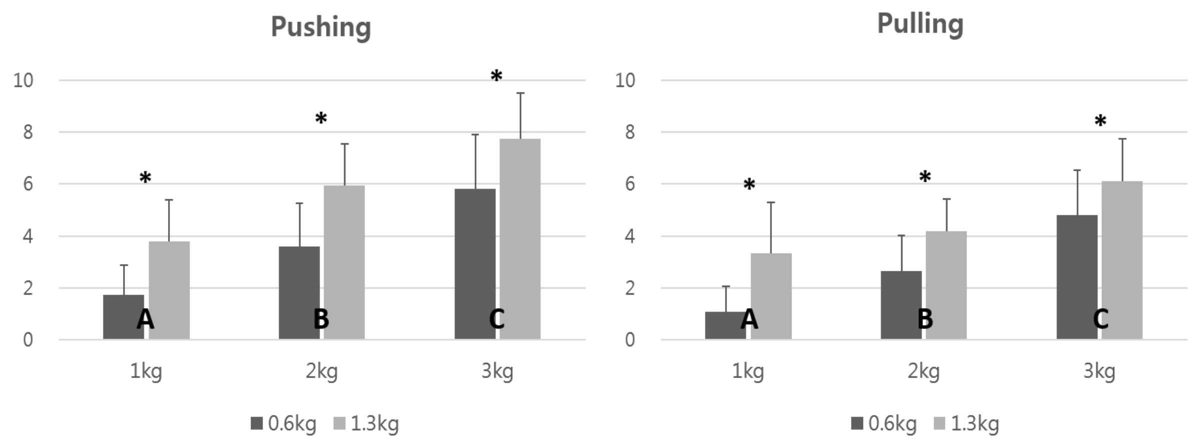

Figure 30. Subjective ratings for weight felt in hand of pushing and pulling task.
(* and bars with different letters indicate significant differences (p<0.05) in post-hoc analysis)

Table 9. Subjective ratings for fatigue and weight felt in hand results summary, Mean (standard deviation) across horizontal load (HL) and vertical load (VL).

Variables		Horizontal load			Repeated measures ANOVA result (F-value; p-value)		
		1kg	2kg	3kg	HL	VL	HL*VL
Push							
Fatigue	Vertical load 0.6kg	2.45 (1.67)	4.35 (1.60)	6.95 (1.54)	157.94; <0.001	69.27; <0.001	1.20; 0.306
	Vertical load 1.3kg	4.20 (1.61)	6.25 (1.94)	8.15 (1.79)			
Weight felt in hand	Vertical load 0.6kg	1.75 (1.12)	3.60 (1.67)	5.80 (2.09)	155.80; <0.001	130.88; <0.001	0.42; 0.657
	Vertical load 1.3kg	3.80 (1.58)	5.95 (1.61)	7.75 (1.74)			
Pull							
Fatigue	Vertical load 0.6kg	1.45 (1.61)	2.75 (1.37)	4.60 (1.43)	54.14; <0.001	41.73; <0.001	1.06; 0.352
	Vertical load 1.3kg	3.40 (1.73)	3.85 (1.46)	6.20 (1.64)			
Weight felt in hand	Vertical load 0.6kg	1.10 (0.97)	2.65 (1.39)	4.80 (1.74)	75.78; <0.001	61.82; <0.001	1.73; 0.183
	Vertical load 1.3kg	3.35 (1.95)	4.20 (1.24)	6.10 (1.65)			

4. DISCUSSION

In this study, activation levels of upper extremity muscles were quantitatively evaluated to figure out the effect of horizontal and vertical loads during dynamic pushing and pulling tasks at submaximal load. The amount of hand grip force and subjective ratings for perceived fatigue and weight were also evaluated. Results indicated that upper extremity and shoulder muscles generated greater activation levels with increased both horizontal and vertical loads during dynamic pushing and pulling tasks, in general. Grip forces and subjective ratings also increased with an increase in two types of loads, complying with the results of muscle activation. This study showed that the results could be applied to designing the consumer products and rehabilitation programs that include submaximal load level of cyclic pushing and pulling.

4.1 Movement tracking

There were no main effects of both horizontal and vertical loads on the movement tracking data of both pushing and pulling tasks. Mean values of peak acceleration while accelerating and decelerating were not significantly different. That is, there was no difference in push/pull movements between conditions that varied by the horizontal and vertical loads. Variation of peak acceleration while pushing and pulling can be interpreted as a velocity profile is variant for the task. Thus, the results of the current study indicate the participants conducted the experiment consistently regardless of both horizontal and vertical loads (Figure 31). It implies that the push/pull force exerted by the participants was caused by two types of external load, not by the acceleration.

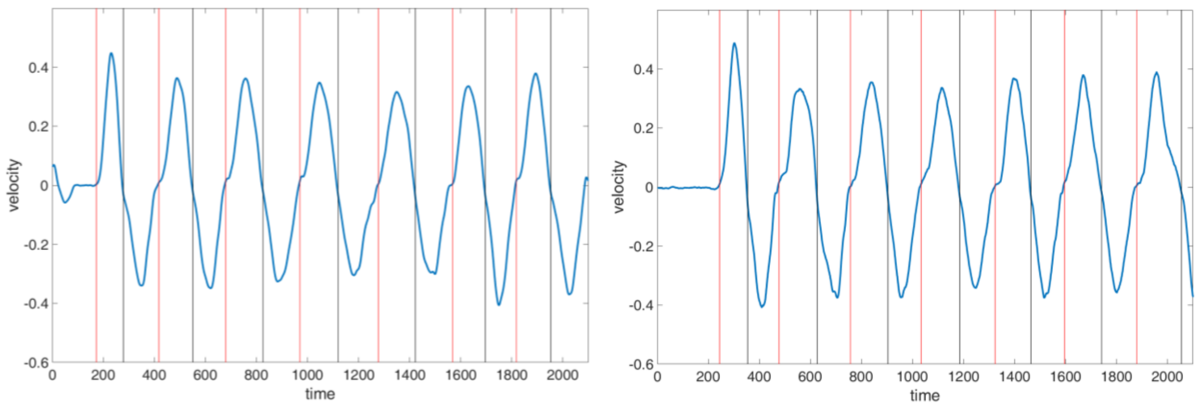

Figure 31. Velocity profile of pulling task with 1kg HL, 0.6kg VL (Left) and 2kg HL, 0.6kg VL (Right). Red and Black vertical lines represent start and end timing of exertion phase respectively.

4.2 Muscle activities

4.2.1 The horizontal and vertical load effects on the muscle activities

Main effects of the horizontal and vertical loads

In the pushing tasks, the normalized muscle activation levels were significantly affected by the horizontal load. Pushing the handle with heavier horizontal load resulted in the greater activation levels of all muscles except brachioradialis muscle, which is similar to that of previous research. Keir and Brown (2012) found that activities of muscles including anterior and posterior deltoids, biceps and triceps brachii, and forearm muscles increased with increasing push load (1kg, 2kg, and 4kg). During pulling tasks, horizontal load effects were found for all muscles except biceps brachii muscle. Pulling the handle with heavier horizontal load generated greater muscle activities of all muscles except anterior deltoid muscle. Exceptionally, participants exerted less anterior deltoid muscle activation level with the increased horizontal load. It might be due to the use of other muscles such as infraspinatus to resist the increased load. When the horizontal load was increased, participants might use other shoulder muscles by externally rotating shoulder rather than using only arm muscles. Thus, anterior deltoid whose role is rotating shoulder internally was less activated with increased load. Results of horizontal load effect indicated that most upper extremity muscles generated greater force to resist the increased horizontal load.

Vertical load effects on muscle activities were also significant for all muscles while conducting both pushing and pulling tasks. Adding vertical load resulted in greater exertions of all muscles except posterior deltoid muscle of pulling tasks. The results of this study supported previous research that found the anterior and posterior deltoid, and upper trapezius muscles showed muscle activation level increase of 21%, 14% and 15%, respectively, as the hand load was increased by 1kg (Sigholm, Herberts, Almstrom, & Kadefors, 1984), and adding about 1kg hand load increased muscle activation of brachioradialis and biceps brachii muscles during flexion and extension of the forearm (Basmajian & Latif, 1957). Holding a weight during shoulder flexion appears to redistribute the muscle activity, increasing the activity of the shoulder muscles (Antony & Keir, 2010). Added hand load increased the moment of shoulder, elbow, and wrist, so participants generated greater activities of all upper extremity muscles to compensate for the increased moment.

Relative impacts of the horizontal and vertical loads

To compare the relative impact of two types of external load on each individual muscle, partial eta squared of both horizontal and vertical loads was calculated and compared in each muscle.

Horizontal load much more affected muscles near the shoulder joint, whose primary roles are pushing/pulling an arm, compared to vertical load. It can be explained by the role of muscles and moment induced by the horizontal load. In the current study, pushing tasks included the shoulder flexion and elbow extension mainly. Anterior deltoid and triceps brachii muscles are known to be used to flex shoulder and to extend forearm at elbow joint, respectively (Tortora & Derrickson, 2006). Pulling consisted of the shoulder extension, elbow flexion, and wrist flexion. The role of flexor carpi ulnaris and posterior deltoid muscles is wrist flexion and shoulder extension, respectively (Tortora & Derrickson, 2006). Therefore, these muscles that acted like primary muscles for pushing/pulling movements responded to the change of horizontal load more apparently to resist induced moment. Forearm muscles were less affected by horizontal load because the forearm was almost parallel to the direction of the applied horizontal load during pushing and pulling, so it might be less affected by the moment that horizontal load generated. Horizontal loads also had more substantial effect on the muscles that are activated as gripping; flexor carpi ulnaris.

The vertical load had much more effect on elbow and shoulder flexors than horizontal load, regardless of exerting direction; pushing and pulling. For both pushing and pulling tasks, brachioradialis and biceps brachii more apparently responded to the change of vertical load compared to horizontal load. Their roles and elbow moment can also explain it. Brachioradialis and biceps brachii is elbow flexors, so they generated eccentric/concentric contraction when extended/flexed elbow joint during pushing/pulling tasks, respectively. Added vertical load increased elbow moment, so more eccentric/concentric contraction forces of elbow flexors were required to maintain the vertical location of the hand in the changes of the moment at the elbow and shoulder joints. In the pulling tasks, anterior deltoid muscle was also more affected by the change in vertical loads. Muscle activation levels of anterior deltoid might respond to increased shoulder moment for the same reason. Keir and his co-workers explained adding the hand load or just elevating or outstretching the arm moves its center of mass away from the shoulder joint, resulting in an increased shoulder moment and consequently increased anterior deltoid activity to compensate for the increased moment (Keir & Brown, 2012; Macdonell & Keir, 2005). Although upper trapezius muscle is not elbow and shoulder flexors, it largely activated to change in vertical load. It might be due to the increased length of the handle. Weight was attached to the bottom of the handle to add vertical load, so participants might tend to elevate shoulder more to avoid touching the frame during tasks with the heavier vertical load.

By way of exception, some muscles had different patterns of relative effect of each load. For pushing task, although the roles of posterior deltoid are not exactly related to the pushing an arm, it was more affected by horizontal load than vertical load. Triceps brachii is also not elbow flexor, but it more apparently responded to vertical load when conducting pulling task. Posterior deltoid and triceps brachii muscle are antagonist of anterior deltoid and biceps brachii muscle, respectively. These muscles were co-activated as antagonist muscles to improve joint stability and stiffness (Andrade, Araújo, Tucci, Martins, & Oliveira,2011). Therefore, they had similar patterns of muscle activation to maintain joint stability when each agonist muscle was more apparently activated by one type of load. It indicated that when the muscles are co-activated as antagonist muscle, the relative impact of each load on the muscle might be determined based on that of their agonist muscles.

In summary, muscles near the shoulder that play primary role for each pushing and pulling were more affected by horizontal load than vertical load. Elbow and shoulder flexors were largely influenced by vertical load that induced moments at elbow and shoulder joints. Responses of the antagonist muscles to the changes in the external loads were more likely to be affected as their agonist muscles being affected by two types of loads.

4.2.2 The interaction effects on the muscle activities

Unlike many previous studies, this study included both horizontal and vertical load variables to find a change in muscle activity due to both factors. However, there were no significant interaction effects between two main factors while conducting pushing task. Previous study found that there was a push load and distal workload interaction in the anterior and posterior deltoids, biceps brachii, and forearm muscles. The addition of the distal workload induced by generating grip force amplified the effect of horizontal load on forearm muscles, but its effect on shoulder muscles reduced as increased horizontal load (Keir & Brown, 2012). Based on the difference between the previous study and the current study, a type of distal workload might be an important role in the interaction effects of horizontal and vertical loads. Although the grip force increased with added vertical loads in this study, it did not have the same effects of the adding grip force as the independent variable in other studies. Also, EMG variables chosen in the current study might affect the results. The only amplitude of electromyography was investigated to figure out the interaction effects. Other variables such as a co-activation index or muscle activation timing may have significant interaction effects between horizontal and vertical loads. Thus, further study should consider various variables from the electromyography data.

For pulling task, significant interaction effects were found, especially for anterior deltoid muscle at median NEMG and triceps brachii muscle at peak NEMG. Activation levels of both muscles were much higher when performing pulling task with 1kg horizontal load and 1.3kg vertical load. It is due to the relative impact of two external loads on the muscles and relative amount of vertical load in total workload. Both anterior deltoid and triceps brachii muscles were affected mainly by the changes of vertical load than that of horizontal load. For these muscles, the effect of adding 0.7kg vertical load to 1kg horizontal load might be relatively larger compared to adding it to 3kg horizontal load, because it is a relatively high proportion of the total workload. For these reasons, less horizontal load amplified the effect of vertical load on anterior deltoid and triceps brachii muscles.

4.2.3 The direction of exertion effects on the muscle activities

To know the direction of exertion (push/pull) effects on the activation level of each individual muscle, post analysis that evaluated the muscle activation data by push/pull tasks was conducted. One-way repeated measures analysis of variance (ANOVA) was used to assess the direction of exertion effects on the muscle activation (significant criterion: $p < 0.05$). There was a significant direction of exertion effect on muscle activation except for biceps brachii at 50th percentile NEMG and upper trapezius muscle at 90th percentile NEMG (Table 10). Consistent with previous study, muscle activation for flexor carpi ulnaris, brachioradialis, and posterior deltoid muscles were significantly greater for pulling tasks. On the contrary, activation levels of anterior deltoid, triceps brachii, and upper trapezius muscles were significantly greater for pushing tasks (Figure 32) (Domizio & Keir, 2010). The major roles of each muscle resulted in the difference between pushing and pulling tasks. Major muscles of each pushing and pulling task more activated when they acted as their primary roles.

Table 10. Results of the statistical analysis for NEMG variables by direction of exertion (F-value; p-value). FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius.

NEMG (% MVC)	Repeated measures ANOVA result (F-value; p-value)						
	FCU	BRA	BIC	TRI	AD	PD	UT
Median NEMG	117.01; <0.001	336.91; <0.001	2.40; 0.123	64.78; <0.001	1133.48; <0.001	68.95; <0.001	14.13; <0.001
Peak NEMG	75.79; <0.001	130.21; <0.001	53.72; <0.001	187.24; <0.001	732.81; <0.001	56.08; <0.001	0.19; 0.663

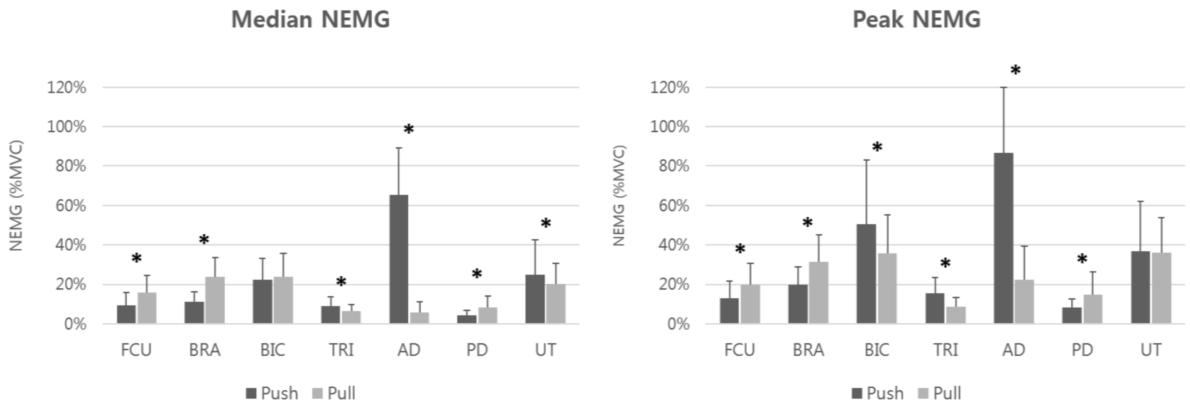

Figure 32. The 50th (Left) and 90th (Right) percentile normalized EMG values by 'Push/Pull'. Error bars indicate 1-standard deviation. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius. (* indicates p < 0.05)

In terms of strength, rather than electromyography data of each muscle, many previous studies measured and compared isometric and isokinetic push and pull strength, indicating that mean maximum pull strength was greater than mean maximum push strength (Seo, Armstrong, & Young, 2010; Yoon, Kim, & Kang, 2011; Das & Wang, 2004; Herring & Hallbeck, 2007). Because the maximum strength of pushing was smaller than pulling in general, the pushing task may require more muscle activation levels compared to performing pulling task with the same load. Although the exact mechanism of force generated by the individual muscle was not known from this study, it is believed that pushing let only specific muscles more activate, not all muscles, than pulling task. Conducting the repeated pushing task may increase the fatigue of specific muscles or cause an unexpected injury.

Findings of subjective ratings supported the difference in muscle activation between pushing and pulling. According to subjective ratings, participants responded that pushing tasks were more physically demanding than pulling tasks. In our post analysis, where the subjective ratings data were evaluated by push/pull tasks, it was found that fatigue was 24% to 69% greater for pushing task, and the weight felt in hand was also 13% to 59% greater for pushing task. It also might be due to different maximal strength between pushing and pulling. Thus, participants felt more fatigue and weight during pushing task than pulling when the same horizontal and vertical loads were given. Therefore, in future studies, it is necessary to consider the difference in muscle activation levels between pushing and pulling in detail, while changing horizontal and vertical load conditions.

4.2.4 Overall explanation and potential applications

Table 11 shows summarized results of each condition that has a relatively greater effect on each individual muscle. It can be applied to design safer and more efficient products or rehabilitation programs that include submaximal load level of push and pull tasks.

Table 11. Summarized results of each condition that has a relatively greater effect on each individual muscle.

Muscles	Horizontal load vs. Vertical load		Pushing vs. Pulling
	Pushing	Pulling	
Flexor carpi ulnaris	Horizontal load	Horizontal load	Pulling
Brachioradialis	Vertical load	Vertical load	Pulling
Biceps brachii	Vertical load	Vertical load	Pushing
Triceps brachii	Horizontal load	Vertical load	Pushing
Anterior deltoid	Horizontal load	Vertical load	Pushing
Posterior deltoid	Horizontal load	Horizontal load	Pulling
Upper trapezius	Vertical load	Vertical load	Pushing

Consumer products_a vacuum cleaner

Findings of muscle activation can be applied to designing consumer products that include repetitive pushing and pulling tasks at submaximal load. For example, when designing a vacuum cleaner, the results of this study can be applied so that users comfortably use the vacuum cleaner for a long time by reducing discomforts and fatigue of users. Weight of the vacuum cleaner can be ideally distributed, and other design elements can be added to adjust the amount of external load. If a muscle that vulnerable to fatigue is more affected by the changes in vertical load, some methods can be used to reduce effects of vertical load on the muscle; to move center of mass of the vacuum cleaner lower, to add a structure that supporting the vertical load, and to rearrange parts for optimized balance by reducing vertical load, and so forth.

When considering re-distribution of the horizontal and vertical loads, there was a relationship of muscle activation levels between conditions. For some muscles, activation levels appear to be consistent across workload (the combination of horizontal load and vertical load). According to Table 12, NEMG of upper extremity and shoulder muscles at a similar workload is quite consistent when comparing the similarly shaded values (blue and green). For example, when pushing at 1kg horizontal load and 1.3kg vertical load, median NEMG of flexor carpi ulnaris was 9.29% MVC versus 8.88% MVC, measured at 2kg horizontal load and 0.6kg vertical load. This pattern was also noted for other workload levels and peak NEMG values as indicated with blue and green shading, and it was more apparent for pushing than pulling tasks. On the contrary, other muscles (shaded as red and orange) had less muscle activation levels when vertical load decreased even though horizontal load increased (Table 12 & 13). Therefore, when applying to vacuum cleaner design, transferring the vertical load to horizontal load can reduce activation of some muscles (red/orange) while maintaining the amount of contraction of other muscles (blue/green).

Table 12. Median (top) and peak (bottom) NEMG values (% MVC) for all seven muscles during pushing task. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius.

Horizontal Load	Vertical Load	FCU	BRA	BIC	TRI	AD	PD	UT
1kg	0.6kg	6.26	8.50	16.33	6.26	48.20	3.15	14.67
	1.3kg	9.29	13.91	22.05	7.77	58.86	4.02	24.32
2kg	0.6kg	8.88	8.53	18.59	7.93	59.95	3.53	20.28
	1.3kg	10.40	13.24	25.88	10.09	72.69	5.03	29.49
3kg	0.6kg	10.29	8.71	21.38	9.73	70.07	4.81	25.48
	1.3kg	11.89	13.67	29.27	11.46	81.74	6.00	35.50

Horizontal Load	Vertical Load	FCU	BRA	BIC	TRI	AD	PD	UT
1kg	0.6kg	8.77	15.34	37.01	11.35	63.83	5.17	23.68
	1.3kg	12.46	24.63	49.59	15.36	80.38	7.54	35.73
2kg	0.6kg	11.92	15.02	43.83	13.21	78.75	6.64	29.47
	1.3kg	14.63	22.89	57.76	17.12	95.12	9.53	42.85
3kg	0.6kg	14.31	16.72	51.11	16.85	93.51	9.04	36.41
	1.3kg	16.77	24.59	64.97	19.03	107.52	11.47	52.11

Table 13. Median (top) and peak (bottom) NEMG values (% MVC) for all seven muscles during pulling task. FCU: Flexor carpi ulnaris; BRA: Brachioradialis; BIC: Biceps; TRI: Triceps; AD: Anterior deltoid; PD: Posterior deltoid; UT: Upper trapezius.

Horizontal Loads	Vertical Loads	FCU	BRA	BIC	TRI	AD	PD	UT
1kg	0.6kg	10.53	17.36	17.27	5.08	5.39	5.00	15.96
	1.3kg	14.22	27.34	30.12	7.11	10.71	5.42	21.69
2kg	0.6kg	13.74	18.81	17.74	5.57	4.13	8.54	15.39
	1.3kg	17.87	27.01	29.17	7.24	5.76	8.10	23.75
3kg	0.6kg	17.97	22.62	19.25	6.52	3.48	12.58	18.64
	1.3kg	21.84	30.22	29.30	7.96	5.94	10.11	26.44

Horizontal Loads	Vertical Loads	FCU	BRA	BIC	TRI	AD	PD	UT
1kg	0.6kg	13.11	22.50	26.54	6.80	21.67	10.18	29.05
	1.3kg	17.59	35.13	45.40	10.10	30.40	8.79	37.23
2kg	0.6kg	17.29	25.02	26.37	7.30	19.07	15.92	28.81
	1.3kg	21.82	35.89	42.73	9.51	25.10	14.25	39.96
3kg	0.6kg	22.33	30.71	28.78	8.93	15.17	22.22	34.41
	1.3kg	26.89	40.00	44.41	10.06	23.74	17.53	46.30

From this relationship, it is expected that muscle activation levels can be affected by some variable, which is the combination of the two external loads. Therefore, future study needs to figure out the variable that represents this relationship.

Difference in muscle activation between pushing and pulling tasks can also be applied to product design. In the case of vacuum cleaners, if muscle that has rapid fatigue occurrence rate is more activated during pushing task, design elements should be considered to make pushing task easier. Adding rotating brush function can be one of the examples for reducing the push load.

Rehabilitation of upper extremity and shoulder muscles

Findings of this study can also be applied to rehabilitation of upper extremity and shoulder muscles and joints. The first application to the rehabilitation is using the results to make guidelines of rehabilitation programs for individual muscle. When patients and clinicians plan to rehabilitate specific muscle, training program and intensity of rehabilitation can be determined based on the relative effects of the conditions for the target muscle. Recently, the paradigms for rehabilitation for upper-extremity motor recovery has been challenged. To improve rehabilitation effect, the medical institution or the rehabilitation facilities are looking for a quantitative and objective rehabilitation method (Lee et al., 2011). Thus, upper extremity rehabilitation systems using robot have been developed for quantitative training recently (Bardorfer, Munih, Zupan, & Primozic, 2001; Koyanagi, Furusho, Ryu, & Inoue, 2003). Lee et al. (2011) have developed the rehabilitation robot that controls the rehabilitation intensity by presenting a virtual force and verified its rehabilitation effect. Optimized rehabilitation programs that are designed for individuals and specific muscles will maximize rehabilitation effect as well as prevent unexpected injury and reduce mental stress of patients.

The second application is to use expanded results of this current study as the database for upper extremity muscle activities of healthy people who do not have any musculoskeletal problems in pushing and pulling tasks. Database for muscle activation patterns of healthy people can be built by expanding the study. Muscle activation patterns of patients who have discomforts on upper extremity muscles may be different from the database when they conduct the same pushing and pulling tasks with the same load condition. Then, it can be figured out which muscle is the problematic muscle, and how this affects other muscle activation levels.

4.3 Grip force

Normalized grip force of pushing and pulling tasks showed a significant increase with horizontal load. Participants exerted greater grip force when conducting pushing and pulling tasks with heavier horizontal load, which is consistent with the previous study. It found that the grip force was modulated in parallel with the amplitude of the imposed push load (Keir & Brown, 2012). Thus, the horizontal load that participants had to generate for push/pull movement probably played a role in grip force as found in previous study.

Normalized grip force also increased as the vertical load was added. Previous study also reported that the grip force required to stabilize the handle was modulated in parallel with hand load

(Flanagan & Wing, 1997). Participants might exert more grip force to maintain stability. They were instructed to perform pushing and pulling tasks at the controlled speed and movement path so that there would be no variability in push/pull strokes. Heavier hand load increased the instability of the arm by increasing the moment of the wrist, elbow, and shoulder. Thus, participants might generate greater grip force to perform stable pushing and pulling tasks without touching the aluminum frame. Therefore, the results of grip force indicated that participants generated grip force according to the amount of task load to resist the push/pull loads and maintain stability.

Grip force can be an independent variable of further study. Many studies have figured out adding a gripping task during shoulder contractions can alert the activation of shoulder muscles, not affecting external torque shoulder (Nakhaie, Nodehi -Moghadam, Bakhshi, Goghatin, & Habebe, 2014). Thus, further study should consider the grip force as independent variables and investigated its effect on muscle activation levels of the upper extremity and shoulder muscles. Findings can be applied to designing the product elements such as a handle to adjust the grip force, resulting in affecting the muscle activation of upper extremity and shoulder muscles.

4.4 Subjective rating

During both pushing and pulling tasks, subjective ratings for fatigue and weight felt in hand showed similar patterns as expected based on previous studies (Keir & Brown, 2012; Hagberg, 1981). Fatigue and weight felt in hand increased as both horizontal and vertical loads increased. The ratio of fatigue and weight felt in hand would be expected to be similar to 1 - 1.74 - 2.52, which is the ratio of the dynamic horizontal load than the ratio between the static load (1kg - 2kg - 3kg). In addition, vertical load effect was mitigated as the horizontal load increased although it is not statistically significant. During pushing task, adding vertical load increased fatigue 71%, 44%, 17%, and weight felt in hand 117%, 65%, 34% when the horizontal loads were 1kg, 2kg, and 3kg, respectively. Similarly, in the pulling tasks, added vertical load increased fatigue 134%, 40%, 35%, and weight felt in hand 205%, 58%, 27% when the horizontal load was 1kg, 2kg, and 3kg. It is estimated that the participants rated discomfort based on the varied horizontal load mainly even though the same vertical load increased. It implied that the evaluation of user discomfort for dynamic push-pull movement should consider dynamic horizontal load, not just static push/pull horizontal load or vertical load.

4.5 Limitations

There were several limitations to be noted in the current study.

Two types of external load had a few levels; horizontal and vertical loads included only three and two levels, respectively, so it is not appropriate to apply to real pushing and pulling tasks immediately. For example, two external loads of the current study were too large for rehabilitation and less than the weight commonly used in consumer products or industries. Although this study found the effects of limited levels of load, findings of current research represented that muscle activation patterns of pushing and pulling tasks at specific submaximal loads can be compared to the result of a further research that includes more diverse levels of external load. Therefore, further research needs to study the effects of more diverse levels on the dependent variables, and to investigate whether the linear muscle activation patterns that were found from this study are still present when the condition levels are more diverse.

Only amplitude of muscle activities was investigated in this study. Other EMG related variables such as fatigue and co-activation index, needs to be considered in the future research. When conducting pushing and pulling tasks of the actual environment, fatigue may be generated even though submaximal pushing and pulling tasks do not cause high muscle activation levels. Previous studies found that high repetition is one of the risk factors for the development of upper extremity musculoskeletal disorders and development of muscle fatigue at repetitive low-intensity tasks (Bosch, Looze, & Dieën, 2007; Ebaugh, McClure,& Karduna, 2006; Roman-Liu, Tokaraski, & Wo´ jcik, 2004). Real pushing and pulling tasks are conducted with high frequency in general, so it may be enough to cause the muscle fatigue. Therefore, future study should investigate the fatigue with a longer task duration for interpolating the results to the real task consisted of reciprocal pushing and pulling.

Also, co-activation index should be considered. Previous study showed that co-activation of the upper extremity muscles was not necessarily generated between agonist and antagonist, reporting that muscles that are closer to exerting muscle had higher correlations (Yamazaki, Suzuki, Ohkuwa, & Itoh, 2002). Co-activation is also expected to be influenced by the condition of load types, posture of the arm, and time. While this study did not investigate other variables such as fatigue and co-activation between muscles, results represented that physical demands of pushing and pulling tasks and protocols of the research can be used as a reference for a further research that considers more specific EMG variables.

Participants might use other muscles such as shoulder, chest, and back muscles. Although participants were instructed to maintain right posture and not rotate their shoulder and trunk for preventing the use of different muscles, they might use them when the task load increased. They would not have performed the tasks by pushing and pulling their arm back and forth, and they might have slightly different postures and movement to resist increased task load. Posture was only monitored by the experimenter who instructs the participants to maintain posture, so there might be subtle biases in pushing and pulling tasks. Therefore, further study needs to investigate the activation levels of other muscles or to trace the trajectory of the arm movement. Also, it needs to be studied to compare the muscle activation levels by adjusting the constraints for other body parts during pushing and pulling tasks.

Although the results of this study are difficult to be used for designing products or rehabilitation programs immediately, test protocols from this study can be used as a reference for future studies, like guidelines. It is expected that this standardized protocol can be useful to reproduce and compare results by quantitatively setting experimental condition. Therefore, test protocols can be used to investigate the effects of not only external loads that were examined in this study but also other influential factors on the upper extremity muscle activities while dynamic pushing and pulling at sub-maximum load level. It can also be used to investigate dynamic movements of other body parts, not just push/pull tasks of the arm.

4.6 Future study

In this study, the physical demands of pushing and pulling tasks were evaluated by investigating the amplitude of muscle activities. During each task of this study, subjects performed seven cycles of push/pull movement, and all dependent variables showed little variation between repetitions. If participants were asked to conduct more cycles of push/pull movements so fatigue would be generated for upper extremity muscles, it might affect the dependent variables of this study. Also, the results of this study showed that all upper extremity and shoulder muscles were simultaneously activated in response to external loads, and there might be a relationship between each muscle. Thus, a future study needs to include other EMG variables such as muscle fatigue and co-activation between muscles during dynamic pushing and pulling tasks.

The current study strictly controlled the characteristics of participants. Only young and healthy females whose height was between 155cm to 168cm participated in this laboratory experiment, so there was no significant difference between participants due to homogeneous participant group, increasing the confidence of study results. However, some precautions are needed to transfer the results of this study to other populations such as male, elderly, and even young and healthy females who have different height. Using protocols referred to this study, it is also possible to figure out the effect of external loads on muscle activation, grip force, and perceived fatigue of other populations. Therefore, further research is needed to study with more various participants whether the linear muscle activation patterns that were found in this study are still present when they conduct the same pushing and pulling tasks.

The results of this study are difficult to be immediately applied to the real fields where the submaximal level of pushing and pulling tasks are used. However, current research figured out the relationship between upper limb muscle activities and the horizontal and vertical loads, and showed how to apply the findings to real pushing and pulling tasks, suggesting that there is a need to expand our understanding. Other factors such as speed, length of strokes, and angle of upper limb joints may affect the upper extremity muscle activities as well as external loads that were evaluated in this study. Findings from such research can be used to make a biomechanical model predicting individual upper extremity and shoulder muscles loading during dynamic pushing and pulling tasks at submaximal load. It can be applied to some real tasks such as designing the products or rehabilitation programs of upper extremity muscles and joints.

5. CONCLUSION

The main goal of this study was to investigate the effect of horizontal and vertical loads on the activation level of upper extremity muscles during dynamic pushing and pulling tasks at submaximal load. Relative impact of two types of external load on each of the seven upper extremity muscles was evaluated and compared to understand the individual roles and characteristics of the muscles while dynamic pushing and pulling. Movement coordinates of the handle, grip force, and perceived fatigue and weight rating measurements during pushing and pulling tasks were also observed. Results of these measurements were analyzed by two-way repeated measures ANOVA with 'participants' as random effects.

Results showed that the relative effects of each external load on individual muscle varied depending on the role of the muscle and moment induced by each load. Muscles near the shoulder joint, which are known as the primary muscles for pushing/pulling movements, responded to the change of horizontal load more apparently. On the contrary, elbow and shoulder flexors were more apparently affected by the change in vertical load to maintain the vertical location of the hand in the changes of the moment at the elbow and shoulder joints. To maintain joint stability, antagonist muscles that do not have major roles for pushing/pulling were more likely to be affected as their agonist muscles being affected by the two kinds of load. During dynamic pushing and pulling tasks, most muscles tested in the current study generated greater activation levels with increased external loads (both horizontal and vertical loads), in general. It might be due to their roles in resisting the increased loads and maintaining the stability of movement in constrained conditions such as speed, movement path, and postures. Grip forces and subjective ratings also increased with an increase in the external load, complying with the results of muscle activation.

This study was the preliminary groundwork in developing a dose-response relationship between horizontal and vertical loads, and upper extremity muscle activation levels. Although precautions are needed to apply the findings of this study to real tasks, the results provided insights into designing products or rehabilitation programs that include submaximal load level of cyclic pushing and pulling. Findings of the current study also indicate the need for further research to expand our understanding of muscle loading with two external loads.

In summary, the key points of this study are,

- Relative effects of horizontal and vertical loads on each individual muscle varied depending on the role of the muscle and moment induced by each load.

a) Muscles near the shoulder were more affected by horizontal load than vertical load.

b) Elbow and shoulder flexors were more apparently affected by vertical load than horizontal load.

c) Responses of antagonist muscles to the changes in the external loads were similar to that of agonist muscles.

- Most upper extremity and shoulder muscles generated greater exertion forces with increased external load both in horizontal and vertical directions during pushing and pulling tasks, in general.

- Study findings and test protocols of this study can be applied to the design and evaluation of consumer products and rehabilitation programs that include dynamic pushing and pulling motions at submaximal load levels.

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APPENDICES

APPENDIX A

<u>Subjective rating questionnaire</u>

Subj #: _______

1.1 실험 후, 신체의 피로도를 평가해주세요.

: 아래 표의 선에 표시해 주시면 됩니다. ** 아령을 들었을 때를 '**5**'로 생각하시면 됩니다!!!

(0) None	Mild	(5) Moderate	Severe	(10) Worst

1.2 실험 후, 손에 느껴지는 무게감을 평가해주세요.

: 아래 표의 선에 표시해 주시면 됩니다. ** 아령을 들었을 때를 '**5**'로 생각하시면 됩니다!!!

(0) None	Mild	(5) Moderate	Severe	(10) Worst

APPENDIX B

Full Analysis of Variance Tables

a. Movement tracking

a.1 Pushing

While accelerating

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	37.3851	1.96764	5.38	< 0.001
Horizontal load	2	0.6042	0.30212	0.83	0.441
Vertical load	1	0.6598	0.65979	1.81	0.182
Horizontal load*Vertical load	2	0.1207	0.06033	0.17	0.848
Error	95	34.7150	0.36542		
Total	119	73.4847			

While decelerating

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	24.2863	1.2782	3.13	< 0.001
Horizontal load	2	0.5896	0.2948	0.72	0.488
Vertical load	1	0.2539	0.2539	0.62	0.432
Horizontal load*Vertical load	2	0.5650	0.2825	0.69	0.503
Error	95	38.7933	0.4084		
Total	119	64.4882			

a.2 Pulling

While accelerating

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	37.0163	1.94822	5.69	< 0.001
Horizontal load	2	0.5960	0.29802	0.87	0.422
Vertical load	1	0.2295	0.22951	0.67	0.415
Horizontal load*Vertical load	2	0.1390	0.06948	0.20	0.817
Error	95	32.5057	0.34217		
Total	119	70.4865			

While decelerating

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	18.3529	0.96594	3.23	< 0.001
Horizontal load	2	0.5042	0.25209	0.84	0.434
Vertical load	1	0.0490	0.04896	0.16	0.687
Horizontal load*Vertical load	2	0.1936	0.09678	0.32	0.724
Error	95	28.4289	0.29925		
Total	119	47.5285			

b. Muscle activities

b.1 Pushing

b.1.1 Median NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.372770	0.019619	33.48	< 0.001
Horizontal load	2	0.022101	0.011051	18.86	< 0.001
Vertical load	1	0.012603	0.012603	21.51	< 0.001
Horizontal load*Vertical load	2	0.001454	0.000727	1.24	0.294
Error	95	0.055673	0.000586		
Total	119	0.464601			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.207922	0.010943	35.14	< 0.001
Horizontal load	2	0.000266	0.000133	0.43	0.653
Vertical load	1	0.075843	0.075843	243.54	< 0.001
Horizontal load*Vertical load	2	0.000254	0.000127	0.41	0.667
Error	95	0.029584	0.000311		
Total	119	0.313869			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.01781	0.053569	31.60	< 0.001
Horizontal load	2	0.07531	0.037655	22.21	< 0.001
Vertical load	1	0.14543	0.145432	85.79	< 0.001
Horizontal load*Vertical load	2	0.00251	0.001255	0.74	0.480
Error	95	0.16105	0.001695		
Total	119	1.40211			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.217780	0.011462	47.34	< 0.001
Horizontal load	2	0.025747	0.012873	53.17	< 0.001
Vertical load	1	0.009770	0.009770	40.35	< 0.001
Horizontal load*Vertical load	2	0.000214	0.000107	0.44	0.644
Error	95	0.023003	0.000242		
Total	119	0.276514			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	4.96299	0.261210	56.08	< 0.001
Horizontal load	2	1.00821	0.504106	108.23	< 0.001
Vertical load	1	0.40960	0.409602	87.94	< 0.001
Horizontal load*Vertical load	2	0.00216	0.001082	0.23	0.793
Error	95	0.44248	0.004658		
Total	119	6.82544			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.050656	0.002666	45.17	< 0.001
Horizontal load	2	0.006733	0.003366	57.03	< 0.001
Vertical load	1	0.004236	0.004236	71.77	< 0.001
Horizontal load*Vertical load	2	0.000198	0.000099	1.68	0.192
Error	95	0.005608	0.000059		
Total	119	0.067431			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	2.94324	0.154907	48.66	< 0.001
Horizontal load	2	0.24184	0.120921	37.98	< 0.001
Vertical load	1	0.27808	0.278085	87.35	< 0.001
Horizontal load*Vertical load	2	0.00033	0.000164	0.05	0.950
Error	95	0.30243	0.003183		
Total	119	3.76592			

b.1.2 Peak NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.664415	0.034969	35.60	< 0.001
Horizontal load	2	0.048551	0.024276	24.71	< 0.001
Vertical load	1	0.026206	0.026206	26.68	< 0.001
Horizontal load*Vertical load	2	0.000851	0.000426	0.43	0.650
Error	95	0.093323	0.000982		
Total	119	0.833347			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.597487	0.031447	16.16	< 0.001
Horizontal load	2	0.005895	0.002947	1.51	0.225
Vertical load	1	0.208823	0.208823	107.30	< 0.001
Horizontal load*Vertical load	2	0.001358	0.000679	0.35	0.706
Error	95	0.184877	0.001946		
Total	119	0.998440			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	10.8490	0.570998	89.91	< 0.001
Horizontal load	2	0.4349	0.217470	34.24	< 0.001
Vertical load	1	0.5432	0.543194	85.53	< 0.001
Horizontal load*Vertical load	2	0.0011	0.000572	0.09	0.914
Error	95	0.6033	0.006351		
Total	119	12.4316			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.553043	0.029108	23.65	< 0.001
Horizontal load	2	0.042635	0.021317	17.32	< 0.001
Vertical load	1	0.033977	0.033977	27.61	< 0.001
Horizontal load*Vertical load	2	0.002100	0.001050	0.85	0.429
Error	95	0.116923	0.001231		
Total	119	0.748678			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	10.1433	0.533860	60.36	< 0.001
Horizontal load	2	1.6152	0.807620	91.32	< 0.001
Vertical load	1	0.7339	0.733890	82.98	< 0.001
Horizontal load*Vertical load	2	0.0040	0.001996	0.23	0.798
Error	95	0.8402	0.008844		
Total	119	13.3367			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.167686	0.008826	29.45	< 0.001
Horizontal load	2	0.030588	0.015294	51.03	< 0.001
Vertical load	1	0.019714	0.019714	65.77	< 0.001
Horizontal load*Vertical load	2	0.000156	0.000078	0.26	0.771
Error	95	0.028473	0.000300		
Total	119	0.246618			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	5.86505	0.308687	38.01	< 0.001
Horizontal load	2	0.42575	0.212876	26.22	< 0.001
Vertical load	1	0.56389	0.563886	69.44	< 0.001
Horizontal load*Vertical load	2	0.00683	0.003417	0.42	0.658
Error	95	0.77143	0.008120		
Total	119	7.63295			

b.2 Pulling

b.2.1 Median NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.664532	0.034975	52.07	< 0.001
Horizontal load	2	0.113670	0.056835	84.62	< 0.001
Vertical load	1	0.045462	0.045462	67.69	< 0.001
Horizontal load*Vertical load	2	0.000097	0.000049	0.07	0.930
Error	95	0.063807	0.000672		
Total	119	0.887568			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.70957	0.037346	31.81	< 0.001
Horizontal load	2	0.03896	0.019478	16.59	< 0.001
Vertical load	1	0.22139	0.221393	188.57	< 0.001
Horizontal load*Vertical load	2	0.00307	0.001537	1.31	0.275
Error	95	0.11153	0.001174		
Total	119	1.08452			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.12515	0.059218	38.06	< 0.001
Horizontal load	2	0.00142	0.000711	0.46	0.635
Vertical load	1	0.39292	0.392925	252.53	< 0.001
Horizontal load*Vertical load	2	0.00395	0.001974	1.27	0.286
Error	95	0.14782	0.001556		
Total	119	1.67126			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.103540	0.005449	66.42	< 0.001
Horizontal load	2	0.002828	0.001414	17.24	< 0.001
Vertical load	1	0.008822	0.008822	107.52	< 0.001
Horizontal load*Vertical load	2	0.000181	0.000090	1.10	0.336
Error	95	0.007794	0.000082		
Total	119	0.123165			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.181685	0.009562	9.84	< 0.001
Horizontal load	2	0.027819	0.013910	14.31	< 0.001
Vertical load	1	0.029546	0.029546	30.40	< 0.001
Horizontal load*Vertical load	2	0.007509	0.003755	3.86	0.024
Error	95	0.092330	0.000972		
Total	119	0.338890			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.256017	0.013475	18.66	< 0.001
Horizontal load	2	0.075305	0.037653	52.15	< 0.001
Vertical load	1	0.002076	0.002076	2.88	< 0.001
Horizontal load*Vertical load	2	0.004440	0.002220	3.07	0.051
Error	95	0.068596	0.000722		
Total	119	0.406435			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.91669	0.048247	27.07	< 0.001
Horizontal load	2	0.03087	0.015437	8.66	< 0.001
Vertical load	1	0.15974	0.159741	89.62	< 0.001
Horizontal load*Vertical load	2	0.00383	0.001913	1.07	0.346
Error	95	0.16933	0.001782		
Total	119	1.28046			

b.2.2 Peak NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.05992	0.055785	57.74	< 0.001
Horizontal load	2	0.17195	0.085973	88.99	< 0.001
Vertical load	1	0.06152	0.061524	63.68	< 0.001
Horizontal load*Vertical load	2	0.00000	0.000002	0.00	0.998
Error	95	0.09178	0.000966		
Total	119	1.38518			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.45870	0.076774	30.33	< 0.001
Horizontal load	2	0.09245	0.046226	18.26	< 0.001
Vertical load	1	0.35839	0.358388	141.56	< 0.001
Horizontal load*Vertical load	2	0.00557	0.002784	1.10	0.337
Error	95	0.24051	0.002532		
Total	119	2.15562			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	3.21535	0.169229	33.22	< 0.001
Horizontal load	2	0.00878	0.004389	0.86	0.426
Vertical load	1	0.86221	0.862213	169.23	< 0.001
Horizontal load*Vertical load	2	0.00574	0.002871	0.56	0.571
Error	95	0.48401	0.005095		
Total	119	4.57609			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.203826	0.010728	31.77	< 0.001
Horizontal load	2	0.003045	0.001522	4.51	0.013
Vertical load	1	0.014765	0.014765	43.73	< 0.001
Horizontal load*Vertical load	2	0.002350	0.001175	3.48	0.035
Error	95	0.032077	0.000338		
Total	119	0.256063			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	2.57847	0.135709	26.74	< 0.001
Horizontal load	2	0.08770	0.043849	8.64	< 0.001
Vertical load	1	0.18150	0.181500	35.77	< 0.001
Horizontal load*Vertical load	2	0.00459	0.002293	0.45	0.638
Error	95	0.48207	0.005074		
Total	119	3.33432			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.09578	0.057673	20.84	< 0.001
Horizontal load	2	0.21648	0.108240	39.11	< 0.001
Vertical load	1	0.02006	0.020059	7.25	0.008
Horizontal load*Vertical load	2	0.00668	0.003342	1.21	0.303
Error	95	0.26290	0.002767		
Total	119	1.60190			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	2.84529	0.149752	26.55	< 0.001
Horizontal load	2	0.11901	0.059507	10.55	< 0.001
Vertical load	1	0.32500	0.325003	57.62	< 0.001
Horizontal load*Vertical load	2	0.00770	0.003851	0.68	0.508
Error	95	0.53587	0.005641		
Total	119	3.83288			

b.3 Direction of exertion effects (Pushing vs. Pulling)

b.3.1 Median NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.8740	0.046000	21.07	< 0.001
Direction of exertion	1	0.2555	0.255483	117.01	< 0.001
Error	219	0.4782	0.002183		
Total	239	1.6077			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.7593	0.039963	13.69	< 0.001
Direction of exertion	1	0.9832	0.983174	336.91	< 0.001
Error	219	0.6391	0.002918		
Total	239	2.3816			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.74129	0.091647	15.07	< 0.001
Direction of exertion	1	0.01457	0.014570	2.40	0.123
Error	219	1.33208	0.006083		
Total	239	3.08794			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.29321	0.015432	31.74	< 0.001
Direction of exertion	1	0.03150	0.031496	64.78	< 0.001
Error	219	0.10647	0.000486		
Total	239	0.43117			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	3.081	0.1622	8.70	< 0.001
Direction of exertion	1	21.133	21.1333	1133.48	< 0.001
Error	219	4.083	0.0186		
Total	239	28.298			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.18893	0.009944	7.64	< 0.001
Direction of exertion	1	0.08971	0.089705	68.95	< 0.001
Error	219	0.28494	0.001301		
Total	239	0.56357			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	3.0404	0.160021	17.47	< 0.001
Direction of exertion	1	0.1294	0.129432	14.13	< 0.001
Error	219	2.0060	0.009160		
Total	239	5.1758			

b.3.2 Peak NEMG

Flexor carpi ulnaris

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.4414	0.075864	21.38	< 0.001
Direction of exertion	1	0.2689	0.268940	75.79	< 0.001
Error	219	0.7771	0.003548		
Total	239	2.4875			

Brachioradialis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	1.7789	0.093627	14.91	< 0.001
Direction of exertion	1	0.8176	0.817607	130.21	< 0.001
Error	219	1.3751	0.006279		
Total	239	3.9717			

Biceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	11.501	0.60531	24.07	< 0.001
Direction of exertion	1	1.351	1.35083	53.72	< 0.001
Error	219	5.507	0.02515		
Total	239	18.359			

Triceps brachii

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.68936	0.036282	25.19	< 0.001
Direction of exertion	1	0.26965	0.269646	187.24	< 0.001
Error	219	0.31538	0.001440		
Total	239	1.27439			

Anterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	9.327	0.4909	14.64	< 0.001
Direction of exertion	1	24.573	24.5728	732.81	< 0.001
Error	219	7.344	0.0335		
Total	239	41.244			

Posterior deltoid

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.8318	0.043777	9.43	< 0.001
Direction of exertion	1	0.2603	0.260349	56.08	< 0.001
Error	219	1.0168	0.004643		
Total	239	2.1089			

Upper trapezius

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	7.6051	0.400268	22.71	< 0.001
Direction of exertion	1	0.0033	0.003349	0.19	0.663
Error	219	3.8607	0.017629		
Total	239	11.4692			

c. Grip force

c.1 Pushing

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.272670	0.014351	13.79	< 0.001
Horizontal load	2	0.185060	0.092530	88.88	< 0.001
Vertical load	1	0.035195	0.035195	33.81	< 0.001
Horizontal load*Vertical load	2	0.000343	0.000172	0.16	0.848
Error	95	0.098899	0.001041		
Total	119	0.592168			

c.2 Pulling

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	0.295754	0.015566	14.61	< 0.001
Horizontal load	2	0.165855	0.082928	77.83	< 0.001
Vertical load	1	0.010410	0.010410	9.77	0.002
Horizontal load*Vertical load	2	0.000383	0.000192	0.18	0.836
Error	95	0.101225	0.001066		
Total	119	0.573628			

d. Subjective ratings

d.1 Pushing

Fatigue

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	220.425	11.601	10.25	< 0.001
Horizontal load	2	357.517	178.758	157.94	< 0.001
Vertical load	1	78.408	78.408	69.27	< 0.001
Horizontal load*Vertical load	2	2.717	1.358	1.20	0.306
Error	95	107.525	1.132		
Total	119	766.592			

Weight felt in hand

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	216.092	11.373	11.07	< 0.001
Horizontal load	2	320.000	160.000	155.80	< 0.001
Vertical load	1	134.408	134.408	130.88	< 0.001
Horizontal load*Vertical load	2	0.867	0.433	0.42	0.657
Error	95	97.558	1.027		
Total	119	768.925			

d.2 Pulling

Fatigue

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	107.958	5.682	3.29	< 0.001
Horizontal load	2	187.017	93.508	54.14	< 0.001
Vertical load	1	72.075	72.075	41.73	< 0.001
Horizontal load*Vertical load	2	3.650	1.825	1.06	0.352
Error	95	164.092	1.727		
Total	119	534.792			

Weight felt in hand

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	131.867	6.940	4.95	< 0.001
Horizontal load	2	212.550	106.275	75.78	< 0.001
Vertical load	1	86.700	86.700	61.82	< 0.001
Horizontal load*Vertical load	2	4.850	2.425	1.73	0.183
Error	95	133.233	1.402		
Total	119	569.200			

d.3 Direction of exertion effects (Pushing vs. Pulling)

Fatigue

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	222.1	11.688	2.37	0.002
Direction of exertion	1	170.0	170.017	34.50	< 0.001
Error	219	1079.3	4.928		
Total	239	1471.4			

Weight felt in hand

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Participants	19	218.88	11.520	2.25	0.003
Direction of exertion	1	69.34	69.337	13.57	< 0.001
Error	219	1119.25	5.111		
Total	239	1407.46			

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